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Phosphate Availability and Supply
A Minerals Availability Appraisal

UNITED STATES DEPARTMENT OF THE INTERIOR

Information Circular 9187

Phosphate Availability and Supply

A Minerals Availability Appraisal

By R.J. Fantel, R.J. Hurdelbrink, D.J. Shields, and R.L. Johnson

UNITED STATES DEPARTMENT OF THE INTERIOR
Donald Paul Hodel, Secretary

BUREAU OF MINES
T S Ary, Director

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering the wisest use of our land and water resources, protecting our fish and wildlife, preserving the environment and cultural values of our national parks and historical places, and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to assure that their development is in the best interests of all our people. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

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PREFACE

The Bureau of Mines, the principal Government agency conducting minerals-related analysis, is charged with assessing the worldwide availability of nonfuel minerals. In so doing, the Bureau identifies, collects, compiles, and evaluates information on active and developing mines, explored deposits, and mineral processing plants worldwide. With this information, the Bureau constructs mathematical mineral models, which it uses to analyze world mineral policy and perform market studies. Objectives are to classify domestic and foreign resources; to identify, by cost evaluation, resources that are reserves; and to prepare analyses of mineral availabilities.

This series of Minerals Availability reports analyzes the availability and supply of minerals from domestic and foreign sources and the factors that affect availability and supply. Analyses of other minerals are in progress. Questions about the Minerals Availability Program should be addressed to Chief, Branch of Minerals Availability, Bureau of Mines, 2401 E Street, NW., Washington, DC 20241.

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

h	hour	mt/yr	metric ton per year
km	kilometer	pct	percent
lb	pound	pct/yr	percent per year
m	meter	$/mt	U.S. dollar per metric ton
m^3	cubic meter	wt pct	weight percent
mt	metric ton	yr	year

PHOSPHATE AVAILABILITY AND SUPPLY

A Minerals Availability Appraisal

By R.J. Fantel,[1] R.J. Hurdelbrink,[2] D.J. Shields,[2] and R.L. Johnson[3]

ABSTRACT

The Bureau of Mines investigated the resources, costs, capacities, market relationships, and short- and long-run supply of phosphate rock and phosphoric acid. The 206 mines and deposits evaluated in 30 market economy countries contain an estimated 35.1 billion mt of recoverable phosphate rock (demonstrated resource level).

U.S. resources are sufficient to satisfy the domestic and export markets for phosphate products well beyond the year 2000. Because of resource depletion at current producers, however, new properties (with higher cost levels) need to be developed if U.S. production levels are to be maintained.

Existing worldwide capacity can satisfy expected demand through the early 1990's. Expansion at existing mines or low demand growth could mean that no new property development will be needed before the late 1990's. Worldwide, almost $8 billion could be required for development of new phosphate rock properties between now and the year 2000, given 3-pct annual growth in demand. Most properties that could develop in the 1990's would require price increases of 20 to 50 pct to break even. To earn a 15-pct rate of return on investment, prices must rise to nearly double the present level of $24 to $29 per metric ton.

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INTRODUCTION

The United States has for many years been the world's largest producer and net exporter of phosphate-related products. U.S. producers are currently facing increased foreign competition for export markets; meeting foreign competition in future years may be even more problematic. This study was undertaken to assess the worldwide availability and supply of phosphate rock, recognizing the critical importance of phosphorus to maintain and enhance agricultural production. The cost of producing phosphate rock in the United States is compared with costs in other phosphate-producing nations, and conclusions are drawn about the future competitiveness of phosphate rock from various sources.

The Bureau of Mines, in its Minerals Availability Program (MAP), has established its expertise in the areas of minerals engineering, cost estimation, and mineral economics. The series of Information Circulars (IC's) on minerals availability has made many of the results of MAP work available to the general public. The data are now being used in computerized engineering-based supply models. These models are analytic tools that put the deposit data on costs, capacities, and resources into a market context, making a wide range of analysis possible. For example, the current competitive position of alternative suppliers to each of the consuming regions can be examined, the impacts of changing economic or engineering parameters can be estimated, resource depletion can be monitored at a pace determined by probable demand levels and growth rates, and the timing of new capacity requirements can be highlighted. Cost comparisons between different potential new supply sources can indicate which are more likely to be developed first and how difficult it will be for the United States to maintain market share.

The "Availability" section of this report provides a summary description of the worldwide deposit-by-deposit data developed for the study. Resource estimates for all major market economy country[4] (MEC) mines and deposits have been established, along with current or proposed production capacities. Production costs and required capital expenditures have also been estimated for each mine or deposit. All of this information is presented in a series of tables, graphics, and availability curves.

The "Supply" section of the report provides an analysis of the phosphate market based on two phosphate supply models that place the deposit data within a market context. These are referred to as the "market balance" and "network flow" models. Production levels in these models are estimated for each deposit, based on least cost criteria. Total production from all deposits is limited each year to the estimated amount of total annual consumption. The pace of resource depletion is dependent on the production level estimates, and new deposits are developed in a timely fashion to maintain a balance of production capability with demand. In the network flow model, the additional costs (and constraints) of intermediate processing and transportation to a final market are accounted for also.

This report is divided into three major sections and a number of appendixes. The first section is a summary description of the phosphate industry worldwide, which brings together information from other sources (primarily Bureau publications) to provide a setting for later analyses. In the second major section, study methodologies are described, and deposit costs and phosphate rock availability are discussed in an abbreviated update of a previous availability report (*1*).[5] In the third section, the results of a set of forecasting and policy analysis model runs are presented, giving estimated phosphate availability and supply through the year 2000.

The appendixes provide additional information on the phosphate industry and the analytical methodologies employed in the study. Descriptive information on all the mines and deposits comprising the data base is presented in appendix A. The phosphoric acid plants are listed in appendix B, and the geology, mining, and processing of phosphate are discussed in appendix C, along with a summary of world phosphate rock resources. The availability methodology is summarized in appendix D, and an extensive description of the supply modeling methodologies is given in appendix E.

Data for the foreign mines and deposits in the evaluation were originally provided by Zellars-Williams, Inc., under Bureau of Mines contract J0100122. New information collected since the previous Bureau IC on world phosphate (*1*) came from a variety of published sources and personal contacts, as well as a British Sulphur Corp. Ltd. consultancy study on Moroccan phosphate deposits (*2*). New data for mines and deposits in the Southeast and Western United States were developed by the Bureau's Intermountain Field Operations Center in Denver, CO, and Western Field Operations Center in Spokane, WA.

ACKNOWLEDGMENTS

The authors wish to thank William F. Stowasser, phosphate commodity specialist, Division of Industrial Minerals, Bureau of Mines, for his assistance in all phases of the work; William Mo, economist, Division of Minerals Policy Analysis, Bureau of Mines, for his work in developing econometric demand equations included in the market models; and Randy Glover, consultant, Management Sciences Systems Software, for his work in adapting the generalized network flow model.

[4] MEC's are defined by the Bureau as all countries that are not centrally planned economy countries (CPEC's). CPEC's comprise the following:

Albania	German Democratic Republic	Mongolia
Bulgaria	Hungary	Poland
China	Kampuchea	Romania
Cuba	Korea, North	U.S.S.R
Czechoslovakia	Laos	Vietnam

[5] Italicized numbers in parentheses refer to items in the list of references preceding the appendixes.

WORLD PHOSPHATE INDUSTRY

Phosphate rock, the only significant commercial source of the element phosphorus, is of vital importance to an expanding agricultural sector worldwide. Phosphorus, nitrogen, and potassium are the three primary nutrients necessary for plant growth. When these elements are either lacking or depleted from the soil, they must be added to reestablish high agricultural yields. Growth of world agricultural production partially depends on the availability of phosphate fertilizers. The use of phosphate in fertilizers accounts for 85 to 90 pct of annual phosphate consumption worldwide (*3*), and therefore, the amount of phosphate rock required in the future will depend primarily on demand from the agricultural sector of the world's economies.

Phosphate rock consists of the calcium phosphate mineral apatite, with quartz, calcite, dolomite, clay, and iron oxide as the gangue constituents. Following industry practice, the term "phosphate rock" is defined in this report as the mined or mined and beneficiated product of phosphate ore rather than the in situ material. After beneficiation, phosphate rock ranges from 26 to 39 pct P_2O_5 (phosphorus pentoxide). Phosphate rock can be converted to phosphoric acid by the wet process or to elemental phosphorus in an electric furnace, or can be applied directly to acidic soils.

Most of the phosphate rock produced in the world is used to manufacture wet-process phosphoric acid. Phosphoric acid is produced by digesting the apatite mineral, i.e., phosphate rock, in sulfuric acid. Diammonium phosphate (DAP), a common bulk blending-grade fertilizer chemical, is produced by reacting phosphoric acid with ammonia. If the phosphate rock is reacted with phosphoric acid, triple superphosphate (TSP) is produced. When wet-process phosphoric acid is subjected to evaporation, a higher concentration of phosphoric acid is produced, and when this is reacted with ammonia, a liquid ammonium phosphate fertilizer is produced (*4*).

A principal nonfertilizer product is phosphate animal feed supplements, produced by the defluorinization of either phosphate rock or phosphoric acid. Phosphate animal feeds are necessary supplements to assure the nutritional quality of livestock diets (*4*).

Industrial products (primarily produced from elemental phosphorus) are the second major category of nonfertilizer use. Elemental phosphorus is produced by reducing phosphate rock in electric furnaces and is marketed as is or oxidized to produce anhydrous derivatives and phosphoric acid. Phosphoric acid produced from elemental phosphorus is principally used to produce sodium tripolyphosphate, a detergent builder.

In combination, the total nonfertilizer uses of phosphate rock account for less than 15 pct of worldwide consumption. In addition, areas such as Brazil and Eastern Europe that have acidic soils can utilize ground phosphate rock for direct application to make limited improvements in soil productivity.

PRODUCTION

Phosphate rock was produced in over 30 countries during 1985 (table 1 and figure 1). The three main producers, the United States, the U.S.S.R., and Morocco, produced 104 million mt, which was 69 pct of the approximately 151 million mt produced worldwide. The world production for 1985 was 6 pct higher than for 1981, 80 pct higher than 1971, and more than three times higher than production in 1961.

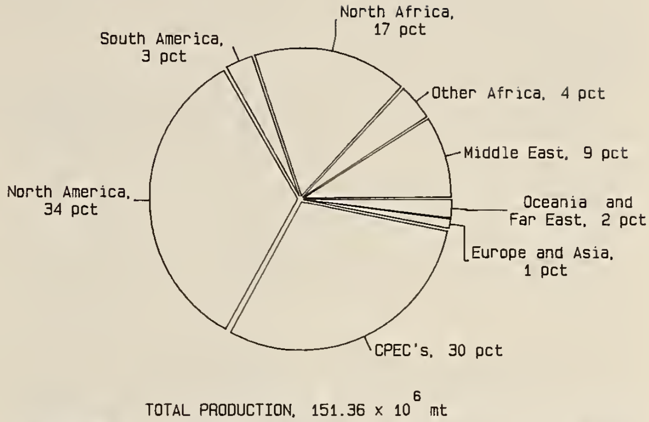

FIGURE 1. — World phosphate rock production, by region, 1985.

Production from MEC's was over 106 million mt during 1985, 70 pct of world production. During 1961 and 1971, MEC production was approximately 78 and 74 pct of total world production, respectively. These figures show a continued decline in the share of world production from MEC's. Figure 2 illustrates the share of world phosphate rock production from the three major producing nations for the years 1961, 1971, 1981, and 1985.

Phosphate production from North America, primarily the United States, was about 51 million mt in 1985, more than 48 pct of total MEC production. During 1961, North America produced about 54 pct of the MEC total and during 1971, over 57 pct. Production from South America was about 4 million mt during 1985, less than 4 pct of total MEC production.

Phosphate rock production from north Africa, over three-fourths of which was from Morocco, was 26.5 million mt during 1985. This was over 25 pct of MEC production, nearly the same percentage as in 1971. The north African share in 1961 was almost 30 pct. Other African countries produced nearly 7 million mt during 1985, 6.5 pct of MEC output. They produced nearly the same percentage of the total in 1971, but less than 3 pct of the total in 1961.

Phosphate rock production from countries in the Middle East area, which includes Egypt, Iraq, Israel, Jordan, Syria, and Turkey, was nearly 14 million mt during 1985. This was 13 pct of MEC production, more than triple the percentage of 1961 and 1971.

Phosphate rock produced in Oceania during 1985 was nearly 3 million mt, more than 2 pct of MEC production. The share of phosphate rock production from this area has declined from almost 6 pct during 1971 and almost 8 pct during 1961.

Phosphate rock production from CPEC's was 45 million mt during 1985. This was about 30 pct of total world production, up from 26 pct during 1971 and 22 pct during 1961. The U.S.S.R. produced about 32 million mt during 1985, 72 pct of CPEC production, and China produced about 12 million mt, 27 pct of the CPEC total.

Table 1.—World production of phosphate rock by region and country for selected years[1]

(Thousand metric tons of product)

Region and country[2]	1961	1971	1981	1985
MEC's:				
North America:				
Mexico	29	58	252	350
Netherlands Antilles (Curacao)	143	156	0	0
United Staes	18,856	35,270	53,624	50,835
Total	19,029	35,484	53,876	51,185
South America:				
Brazil	659	200	3,238	4,214
Chile	14	0	98	0
Colombia	0	10	17	23
Peru	0	0	0	12
Venezuela	0	25	0	0
Total	674	235	3,353	4,249
North Africa:				
Algeria	440	495	916	1,207
Morocco and Western Sahara	7,949	12,006	18,562	20,737
Tunisia	1,981	3,161	4,596	4,530
Total	10,370	15,662	24,074	26,474
Other African Countries:				
Senegal	547	1,545	1,699	1,702
South Africa, Republic of	297	1,233	2,718	2,421
Tanzania	0	0	0	15
Togo	118	1,715	2,215	2,452
Uganda	0	16	0	0
Zimbabwe	0	105	125	131
Total	961	4,614	6,757	6,721
Middle East:				
Egypt	627	713	720	1,074
Iraq	0	0	50	1,000
Israel	226	765	1,919	4,076
Jordan	423	569	4,244	6,067
Syria	0	6	1,321	1,270
Turkey	0	0	43	37
Total	1,275	2,053	8,297	13,524
MEC's—Continued				
Oceania and Far East:				
Australia	5	6	22	34
Christmas Island[3]	705	990	1,423	1,200
Indonesia	10	0	8	3
Kiribati (Banaba Island, formerly Ocean Island)	343	619	0	0
Makatea Island (French Oceania)	381	0	0	0
Nauru	1,303	1,867	1,480	1,508
Philippines	0	5	8	(4)
Total	2,747	3,487	2,941	2,745
Europe:				
Belgium	14	0	0	0
Finland	0	0	201	510
France	81	19	0	0
Germany, Federal Republic of	0	60	0	0
Sweden[5]	0	0	124	187
Total	95	79	325	697
Asia:				
India	20	243	562	748
Sri Lanka	0	0	15	17
Thailand	0	0	6	3
Total	20	243	583	768
Total MEC's	35,172	61,856	100,206	106,363
CPEC's:				
China[e]	508	2,177	11,500	12,000
Korea, North[e]	152	272	500	500
Poland	47	0	0	0
U.S.S.R.[e]	8,799	19,002	30,700	32,200
Vietnam[e]	622	553	181	300
Total CPEC's	10,127	22,004	42,881	45,000
Total world	45,299	83,860	143,087	151,363

[e]Estimated.
[1]Purely guano or basic slag deposits not included.
[2]Some countries' production is listed as zero although small quantities were produced (e.g., Belgium and Uganda), and some countries are not listed because only small quantities were produced.
[3]Australian territory.
[4]Not available in 1985. Minor quantities reported produced in 1984.
[5]Swedish material is byproduct apatite concentrate derived from iron ore.

NOTE.—Data may not add to totals shown because of independent rounding.
Sources: British Sulphur Corp. Ltd. (*2*); BuMines Minerals Yearbooks 1963, 1973, 1984, and 1985 (*5-8*), chapter on Phosphate Rock.

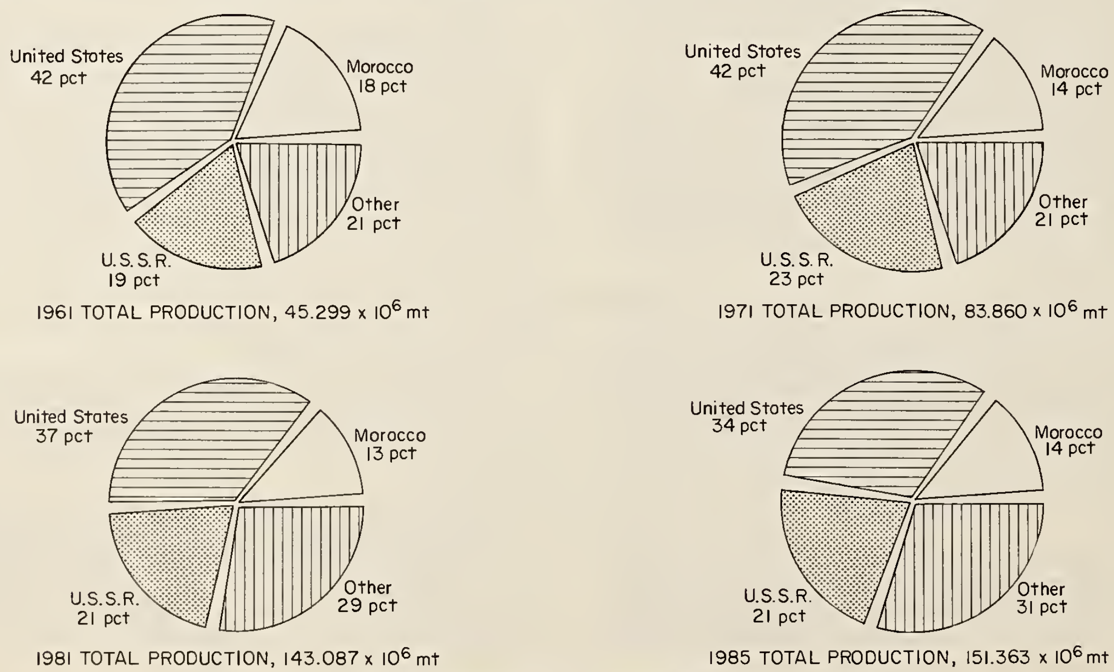

FIGURE 2. — World phosphate rock production shares for selected years.

CONSUMPTION

Consumption of phosphate can be broadly classified into fertilizer and nonfertilizer uses. By far the most important use is for a wide variety of fertilizer products. Historically, 90 to 95 pct of phosphate use is in this form.

Fertilizer consumption levels for selected years between 1965 and 1985 are shown in table 2 and figure 3. Over that period there was a moderate growth of consumption in the United States and Western Europe and more substantial growth in all other regions. The U.S. phosphate fertilizer consumption level grew from 3.3 million mt (contained P_2O_5) in 1965 to a peak of 4.9 million mt in 1980 but was at lower levels afterward. The regions with the highest absolute growth since 1965 were Oceania and Asia, whose usage went from 3.0 million mt in 1965 to 9.7 million mt in 1985. Other regions with very high growth rates include Latin America, Africa, and the U.S.S.R., all of whom consumed more than four times as much phosphate fertilizer in 1985 as they did in 1965.

Table 2.—Consumption of phosphate, fertilizer, for selected years

(Thousand metric tons of P_2O_5)

Consuming region	1965	1970	1975	1980	1985
North America:					
United States	3,348	4,251	4,418	4,928	4,270
Canada	300	305	502	630	530
Latin America	446	843	1,677	2,607	2,480
Africa	342	526	794	1,017	1,500
Oceania and Asia	3,011	3,984	5,010	7,655	9,700
Western Europe	4,353	5,336	5,002	5,652	6,200
Eastern Europe	1,386	2,189	2,990	3,280	3,300
U.S.S.R.	1,394	2,063	4,444	5,535	7,200
Total	14,580	19,497	24,837	31,304	35,180

Sources: 1965-80 values, FAO Annual Fertilizer Review (*9*); 1985 values, Zellars-Williams, Inc. (*3*).

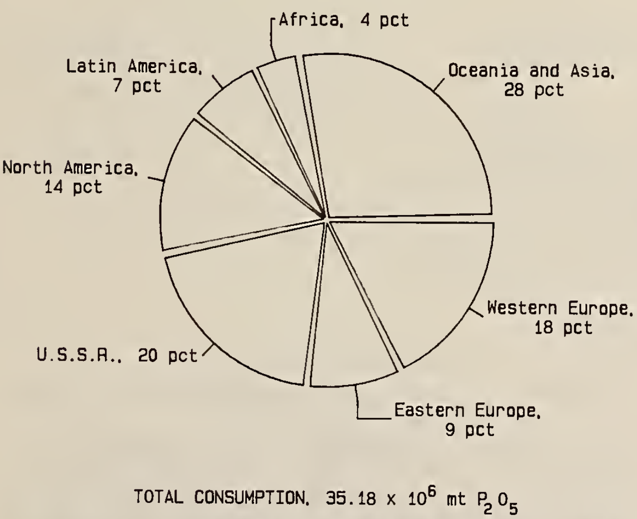

FIGURE 3. — Consumption of phosphate fertilizers, by region, 1985.

Projections of future fertilizer consumption levels are required for the market models used for analyses later in this report. These projections are based on extrapolation of past trends using statistically estimated functions that can depend on world economic activity levels. The amount of phosphate rock required in the future to satisfy estimated demand will depend on the form of that demand and the extent of phosphate losses incurred in processing and handling. Losses can be very low for material applied directly to the soil but can get higher when phosphate rock is processed into complex fertilizer chemicals. The amount of processing losses depends on the technology used to convert the material into fertilizer and the efficiency of transportation and handling. The choice of technology can depend on the nature of the phosphate ore, the needs of the consuming region's soil, the availability of other inputs to the processes that result in fertilizer products, and other considerations (*10*).

Nonfertilizer uses of phosphate are grouped into two major categories: animal feed supplements and industrial uses (i.e., uses of primarily elemental phosphorus and its derivatives). Consumption levels in recent years for both categories are shown in table 3.

Table 3.—Consumption of phosphate, nonfertilizer, for selected years

(Thousand metric tons of P_2O_5)

Consuming region	1970	1975	1980	1985
ANIMAL FEED SUPPLEMENTS				
North America:				
United States	496	387	528	550
Canada	30	42	63	60
Latin America	4	8	28	46
Africa	26	35	40	45
Oceania	0	0	2	2
Asia	81	128	199	252
Western Europe	268	332	453	470
Eastern Europe	56	104	156	170
U.S.S.R.	51	346	432	650
Total	1,012	1,382	1,901	2,245
INDUSTRIAL USES				
North America:				
United States	886	694	676	660
Canada	35	42	52	50
Latin America	75	138	189	243
Africa	23	34	50	75
Oceania	12	16	19	21
Asia	121	165	234	353
Western Europe	537	655	731	745
Eastern Europe	58	109	145	160
U.S.S.R.	51	82	108	150
Total	1,798	1,935	2,204	2,457

Source: Zellars-Williams, Inc. (*3*).

Use of phosphates in mineral food supplements is more concentrated in areas of the world where livestock management is practiced, with poultry, swine, and dairy and feed cattle all using large amounts of inorganic phosphates to maintain a balanced diet. Principal examples of industrial uses include detergent builders, cleaners, and water treatment. Other industrial uses, although not major in terms of volume, include some of the highest valued and most specialized of all phosphate applications. Examples include leavening agents, plastic stabilizers, medicines, human food supplements, toothpaste, coffee creamers, rubber production, and inhibitor systems for antifreeze.

Table 4.—International trade in phosphate rock, 1983-85

(Thousand metric tons of product)

Exporting source and destination of exports	1983	1984	1985
Algeria and Tunisia:			
Asia	20	256	217
Eastern Europe	846	869	890
Western Europe	722	558	633
Other	0	50	210
Total	1,588	1,733	1,950
Israel and Jordan:			
Asia	1,694	2,718	3,095
Eastern Europe	1,454	1,766	1,671
Oceania	80	113	67
Western Europe	2,148	2,141	2,071
Other	0	0	19
Total	5,376	6,738	6,923
Morocco:			
Asia	1,385	1,546	1,612
Canada	0	0	22
Eastern Europe	2,760	2,210	2,800
Latin America	802	823	877
Oceania	35	94	96
Western Europe	9,445	10,303	9,369
Total	14,427	14,976	14,776
Oceania and Far East:			
Australia	1,687	1,419	1,424
Indonesia, Republic of Korea, Malaysia, China, Singapore, and Japan	116	414	605
New Zealand	756	759	667
Total	2,559	2,592	2,696
Senegal:			
Asia	315	282	365
Eastern Europe	57	112	78
Western Europe	877	939	789
Other	0	27	22
Total	1,249	1,360	1,254
Togo:			
Asia	20	76	126
Eastern Europe	799	783	567
Western Europe	1,174	1,786	1,612
Other	0	115	140
Total	1,993	2,760	2,445
U.S.S.R:			
Eastern Europe	3,701	3,467	3,060
Western Europe	1,193	911	888
Other	0	5	0
Total	4,894	4,383	3,948
United States:			
Africa	0	89	0
Asia	3,498	3,401	3,277
Canada	2,648	3,380	2,591
Eastern Europe	863	1,004	830
Latin America	440	473	341
Oceania	390	288	334
Western Europe	3,776	3,074	2,909
Total	11,615	11,709	10,282

Sources: 1983 values, BuMines Mineral Facts and Problems, 1985 (*11*); 1984-85 values, International Fertilizer Industry Association Ltd. (*12-13*).

TRADE

World trade in phosphate rock for the 1983-85 period is shown in table 4. The 1985 values are illustrated on figure 4. The table shows the destination of phosphate rock from major exporting countries to the major importing areas of each. This table shows exports only. The phosphate rock not exported directly by country is either consumed domestically or exported after further processing.

Comparing 1985 production quantities in table 1 with trade quantities in table 4 shows that the United States exported over 10 million mt of phosphate rock, or 21 pct of its production, a relatively low percentage compared with those of the other major MEC exporters. Morocco exported over 14 million mt of phosphate rock, more than 70 pct of its production. Algeria and Tunisia together exported more than 1.9 million mt in 1985, 34 pct of their combined production. Isreal and Jordan together exported nearly 7 million mt in 1985, almost 70 percent of their combined production. Senegal exported over 1.2 million mt, 70 pct of its 1985 production. Togo exported 2.4 million mt, almost all of its production for 1985. The U.S.S.R. exported nearly 4 million mt, just over 12 pct of its 1985 production. Oceania and the Far East exported about 2.7 million mt, nearly all of their production for 1985.

These numbers reflect rates of domestic consumption and the amount of capacity to further process phosphate rock into phosphoric acid or fertilizer products in the various countries. The United States has been for many years an industry leader in the processing of phosphate rock and the export of higher-value-added forms of phosphate. The recent trend, however, has been for more of the rock producing countries to develop phosphoric acid capacity and to export higher-value-added products. Morocco, which now exports mostly unprocessed phosphate rock, has just completed a major fertilizer plant at Jorf Lasfar. Other countries that have made public pronouncements to increase value-added capacity for their phosphate exports include Togo (depending on the availability of financing) and Tunisia.

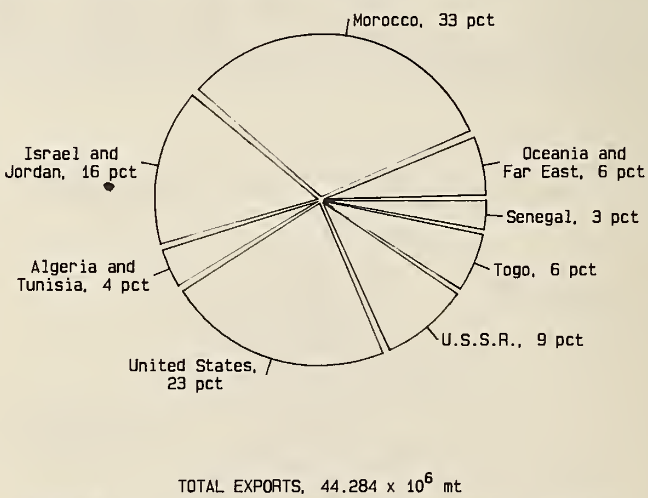

FIGURE 4. — Principal exporters of phosphate rock, 1985.

The United States exported significant quantities of chemical phosphate products during 1984, the latest year for which complete data are available. Table 5 and figure 5 show exports of processed phosphate products from the United States and other countries. Excluded from the table are all phosphate products that are consumed within the country in which they are manufactured. Included in the table and figure are reexports from countries that must im-

Table 5.—Processed phosphate exports, 1984

(Thousand metric tons of P_2O_5)

Exporting source and destination of exports	Phosphoric acid	Triple superphosphate	Ammonium phosphates
ROCK PRODUCERS			
Jordan:			
Africa	0	0	26
Asia	32	0	185
Oceania	0	0	10
Western Europe	0	0	23
Total	32	0	244
Morocco:			
Africa	0	7	0
Asia	741	103	0
Eastern Europe	6	37	0
Latin America	34	0	0
Western Europe	300	62	36
Total	1,081	209	36
Senegal:			
Africa	0	0	9
Asia	55	0	0
Western Europe	5	3	0
Total	60	3	9
South Africa, Republic of:			
Africa	0	0	4
Asia	62	0	11
Latin America	69	0	2
Oceania	0	0	18
Western Europe	81	0	13
Total	212	0	48
Tunisia:			
Africa	0	14	30
Asia	251	59	54
Eastern Europe	6	16	5
Latin America	0	10	0
Western Europe	77	93	112
Total	334	192	201
ROCK PRODUCERS—Continued			
United States:			
Africa	0	8	52
Asia	274	51	1,923
Canada	45	95	101
Eastern Europe	521	80	46
Latin America	185	143	374
Oceania	0	34	149
Western Europe	45	98	538
Total	1,070	509	3,183
REEXPORTERS			
Korea, Republic of:			
Africa	0	0	14
Asia	0	0	181
Western Europe	0	0	42
Total	0	0	237
Turkey:			
Africa	0	12	0
Asia	0	41	16
Eastern Europe	0	14	0
Western Europe	0	9	0
Total	0	76	16
Western Europe:[1]			
Africa	0	0	12
Asia	52	0	11
Eastern Europe	85	0	0
Latin America	1	0	0
North America	([2])	0	4
Western Europe	301	169	179
Unknown	1	30	20
Total	440	199	226

[1]Includes Belgium, Finland, France, Netherlands, Spain.
[2]Quantity was less than 1 unit.

Source: International Fertilizer Industry Association Ltd. (*14*).

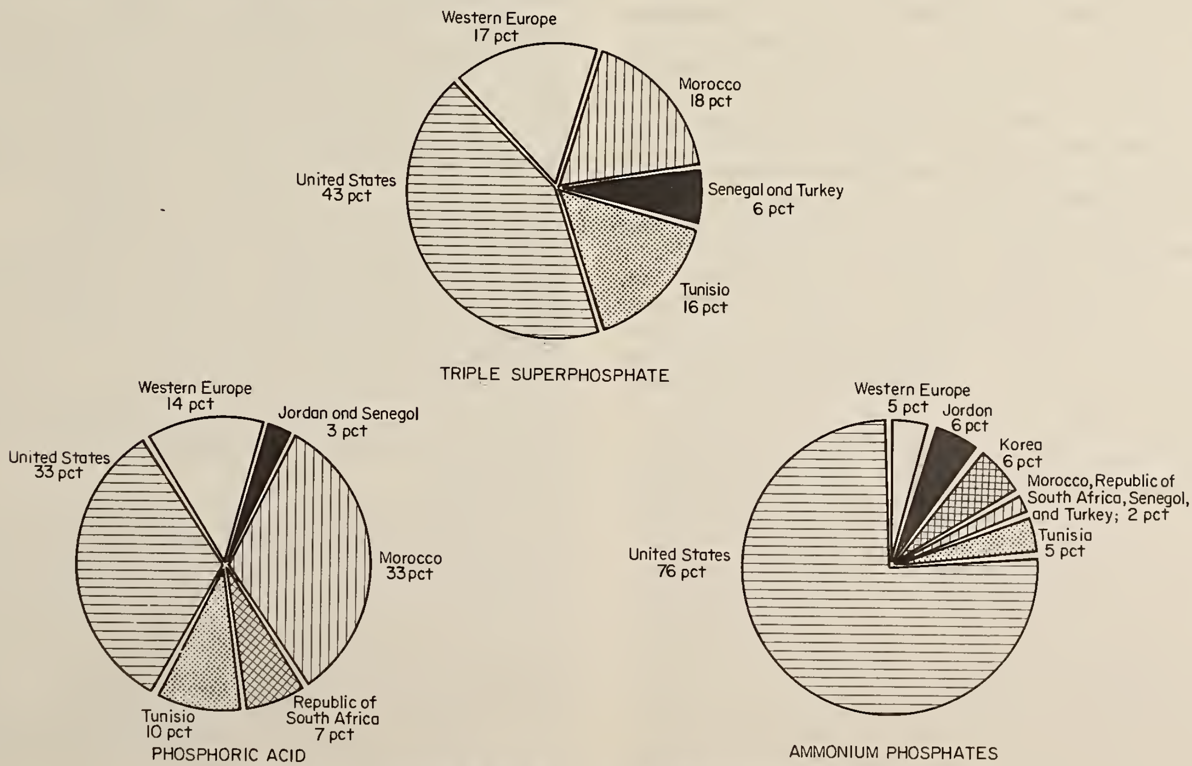

FIGURE 5. — Principal exporters of phosphate fertilizer products, 1984.

port the phosphate rock used to make these phosphate products. These are primarily Western European countries trading within Western Europe and the Republic of Korea, which exports to its Asian neighbors.

As can be seen from the information contained in table 5, the United States is the largest exporter of processed phosphates. Morocco is a major exporter of phosphoric acid and triple superphosphate. Tunisia exports a substantial amount of all three products, and its total processed phosphate exports are a large percentage of its total phosphate rock production level.

Also apparent from table 5 is that Asia (primarily India, Japan, and China) is the biggest import market for processed phosphates. These countries are the principal destinations for processed phosphate products from Jordan, Morocco, Senegal, Tunisia, the United States, and the Republic of Korea. The market for processed phosphates is in sharp contrast to the export market for phosphate rock (see table 4), where Western Europe is the biggest importer. This reflects the fact that Europe has a large number of phosphate fertilizer plants and is able to convert imported rock into various fertilizer products.

Figure 6 shows the combined exports of phosphate in all product forms for each of the major phosphate-rock-producing countries exporting in 1984. Phosphate rock exports shown in table 4 have been converted to P_2O_5 content and combined with the exports of processed forms of phosphate reported in table 5. It is apparent that the United States is the world's largest exporter of phosphate when all product forms are combined. Also apparent is that (with the exception of the United States, Morocco, and Tunisia) most of the phosphate trade in the world is in the form of phosphate rock, also the trend is toward an increasing trade of processed phosphates.

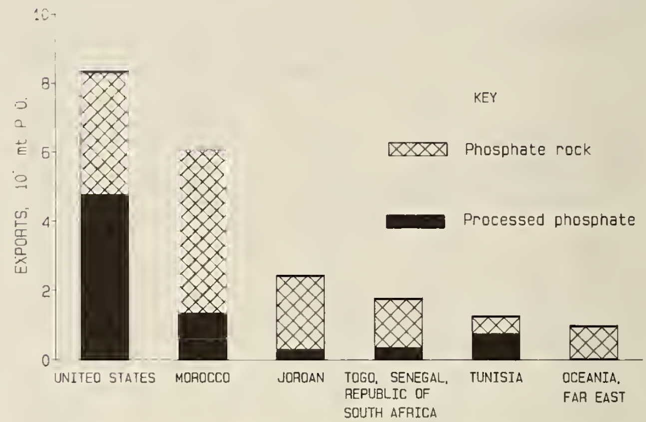

FIGURE 6. — Principal MEC exporters of phosphate rock and processed phosphate, 1984.

METHODOLOGIES AND COST DATA

METHODOLOGIES

Cost Estimation and Data Development

The costs used in this study were collected or developed using various methodologies. All values are in terms of January 1985 U.S. dollars. Costs for the developed deposits in the Southeast United States (including Florida, North Carolina and Tennessee) were collected or estimated by the Bureau's Intermountain Field Operations Center in Denver, CO. Data for most of the undeveloped properties in the Southeast United States were based on the work done by Zellars-Williams, Inc., under Bureau contract. Costs for all deposits in the Western United States (Idaho, Montana, Utah, and Wyoming) were collected or developed by the Bureau's Field Operations Centers in Denver, CO, and Spokane, WA, using engineering expertise and various methodologies such as scaling from known values, the Minerals Availability System (MAS) cost estimating system (CES) (*15*), and actual reported company data.

The costs of deposits in other countries were originally collected or developed by Zellars-Williams, Inc., under Bureau contract. Some of the costs for Morocco were updated based on a report by British Sulphur Corp. Ltd., London (*2*). Some of the foreign deposit costs are actual company-reported data, although most were developed using the contractor's computerized model. This cost model uses data on labor, equipment, and supplies, which are site-specific for each deposit. Estimates are made of actual quantities and unit costs for each variable, based on local rates at each deposit. The Bureau's economic index system is used to update all cost estimates to a common measure. The final product of this model is a unit cost for each portion of the mining and milling operation.

Capital expenditures were calculated for exploration, acquisition, mine plant and equipment, constructing and equipping the mill plant, and all necessary reinvestment in mine or mill. Capital expenditures for mining and processing facilities include the costs of mobile and stationary equipment, construction, engineering, facilities and utilities (infrastructure), and working capital. The facilities and utilities category includes the cost of access and haulage facilities, water facilities, power supply, and personnel accommodations. Working capital is a revolving cash fund required for such operating expenses as labor, supplies, taxes, and insurance. For this study, working capital was estimated as 2 to 3 months of operating costs.

Mine and mill operating costs for each deposit are calculated in local currencies and then converted to U.S. dollars. Operating costs are a combination of direct and indirect costs. Direct operating costs include materials, utilities, direct and maintenance labor, and payroll overhead. Indirect operating costs include technical and clerical labor, administrative costs, facilities maintenance and supplies, and research. Other costs in the analysis are fixed changes, which include mainly local taxes and insurance.

Transportation charges are derived from actual data when available or are estimated from data for other products in the same geographical area. The in-country transportation cost required to get phosphate rock to a port (for possible export) or to a phosphoric acid plant (for further processing) is included in the "Cost Data" section. The ocean freight charges incurred in moving phosphate products to final markets are included only in the network flow model.

Acidulation costs (estimated for all facilities included in the network flow model) are comprised of separate estimates for sulphur, electric power, labor, supplies, water,

fuel, and waste disposal. Credits for steam generated in some operations are accounted for where applicable. Phosphoric acid plant production costs are used only in the network flow model. The cost of phosphate rock feed to the various phosphoric acid plants (and the source of the feed) is derived as part of the optimal solution of the network, but all other elements of variable cost are specified prior to solution. (A listing of phosphoric acid plants is provided in appendix B.)

The Bureau's economic index system was used to update cost estimates (as necessary) to a base date (January 1985 for this report). The index system includes updating factors for 12 separate components of mining cost (e.g., mining labor, mining equipment, diesel fuel) for foreign countries and 15 components for the United States. The index values for each component in each country take account of whether the expenditure is in local or foreign currency and what the traditional sources are for needed imports such as machinery. A time series of exchange rates (also part of the index system) is used to translate the cost index values developed in local currencies into values expressed as U.S. dollars.

Availability Estimation

After capital and operating costs are determined, deposit data are entered into the supply analysis model (SAM). The Bureau developed the SAM to perform discounted-cash-flow rate of return (DCFROR) analyses to determine the price of the primary commodity required so that each operation obtains a specified rate of return on its investments (*16*). This determined value for the phosphate rock price is equivalent to an average total cost of production for the operation over its producing life under the set of assumptions and conditions (i.e., mine plan, fill-capacity production, and a market for all output) necessary in order to make an evaluation. The DCFROR is most commonly defined as the rate of return that makes the present worth of cash flow from an investment equal the present worth of all after-tax investments (*17*). For this study, a 15-pct DCFROR was considered the necessary rate of return for operations to cover the opportunity cost of capital plus risk. A DCFROR analysis for each property was also performed with a 0-pct rate of return, and both sets of results are presented later in the "Availability" section.

For purposes of the DCFROR methodology, all capital investments incurred 15 yr before the initial year of analysis (January 1985) are treated as fully depreciated costs. Capital investments incurred less than 15 yr before January 1985 have the undepreciated balances carried forward to January 1985. All subsequent investments, reinvestments, operating costs, and transportation costs are expressed in January 1985 dollars.

A separate tax records file, maintained for each State or nation, contains the relevant parameters under which the mining firm would operate. Tax parameters include structures and rates for corporate income taxes, property taxes, and any royalties, severance taxes, or other taxes that pertain to phosphate rock production. These tax parameters are applied to each mineral deposit under evaluation, with the implicit assumption that each deposit represents a separate corporate entity.

Upon completion of the individual property analyses, all 206 properties included in the study were sequentially aggregated onto resource availability curves. Two types of resource availability curves have been generated for this study: (1) total availability curves and (2) annual availability curves.

The total resource availability curve is a tonnage-cost relationship, which shows the quantity of recoverable product potentially available at each operation's average total cost of production, as determined at the specified (15-pct) DCFROR. Thus, the curve is an aggregation of the total potential phosphate rock that could be produced over the entire producing life of each operation, ordered from operations with the lowest average total cost of production to those with the highest. The curve provided a concise, easy-to-read, graphic analysis of the comparative costs associated with any given level of potential output.

Annual availability curves are simply a disaggregation (using installed capacity instead of total tonnage) of the total curve to show annual phosphate rock availability at varying total costs of production. These curves show (for the near term) the maximum annual production capacity from current producers and the maximum amount of new production capacity that could become available at various lead times necessary for development.

Certain assumptions are inherent in the curves. First, all deposits produce at full operating capacity throughout the productive life of the deposit. Second, each operation is able to sell all of its output at a price equal to its average total production cost. Third, development of all nonproducing deposits begins in a base year N (unless the property was developing at the time of the evaluation or definite startup dates were known). No assumption is made about circumstances that might lead property owners to develop the various mines. In almost all cases, the preproduction period allows for only the minimum engineering and construction necessary to initiate production under the proposed development plan. Consequently the additional time lags and potential costs involved in filing environmental impact statments, receiving required permits, financing, etc., have not been included in the individual deposit analyses. This third assumption is incorporated in all MAP studies to show minimum development time in periods of national need.

Market Balance Model

The market balance model presented in this study is a world market model for phosphate that incorporates supply, demand, and price into a larger framework within which supply estimates can be made. The emphasis has been placed on the development of logical, defensible supply models that utilize the detailed deposit-specific data base (described in the two previous sections on cost and availability) in making projections of the amount of material likely to be supplied to the market under a variety of different market conditions.

Supply for MEC's represents annual production amounts from demonstrated resources at mines and deposits with installed capacity. Production from CPEC's is determined exogenously, and deposit data are only used to verify that specified production levels are attainable.

Total supply is equal to the aggregate of annual production from the installed capacity at developed deposits. Cost levels at each of the MEC deposits are used in the determination of individual annual production levels. The production capacity and resource numbers presented later in the "Availability" section are the upper limits on how much primary supply is available from each MEC deposit in a single year and over a series of years.

The market balance model is a systems simulation model (*18*) that establishes an annual balance of world sup-

ply and world demand by finding an equilibrium market price. The balance is made at a global level, with total demand for P_2O_5 in all product forms equal to the total P_2O_5 content of phosphate rock available at various transshipment points, after accounting for processing and handling losses. As they are represented in the model, both supply and demand can respond to changes in market price. The estimated production at each deposit is subtracted from the remaining resources each year until an ore body is depleted. Available deposits are developed in a timely fashion to maintain an approximate balance of capacity with consumption over time.

The market balance model is useful in examining questions of resource adequacy over the medium to long term, under various scenarios concerning likely future demand levels. The magnitude and timing of new capacity requirements and the capital needed to finance development are monitored. The average total cost levels at new mines will correspond to an expected future market price, or incentive price, that different property owners might be anticipating when they make development decisions. Total costs are not included in the simulation model except to set priorities on which properties are triggered to develop first.

Network Flow Model

The network flow model is a single-year optimization model (*19*). It takes account of the trade flows as material goes from ore in the ground at specific deposits to final products consumed in various world regions. Transportation and intermediate processing are more fully incorporated into this model than they are in the market balance model. The network flow model provides a pattern of production and material flow that satisfies all regional demands at a minimum total system cost (i.e., all variable costs incurred in satisfying worldwide demand). The network flow model can be made to solve for a series of years by using the logic of the market balance model to deplete resources, bring on new capacity, and alter costs of production and other deposit-specific data on a year-to-year basis as appropriate.

The network flow model is well suited to answering questions related to regional competition, production, and trade flows. Since detailed material flows are solved for, such things as regional trade barriers can be incorporated into the model directly as constraints.

Both model forms (market balance and network flow) are described in more detail in appendix E, and the manner in which the models are able to exploit the availability data base is also addressed. Topics such as how additional supply-side data can be utilized, how demand estimates are generated and incorporated into the models, and how the model solutions are to be interpreted are given extensive treatment in appendix E.

COST DATA

Figure 7 summarizes many of the cost data developed for the producing properties included in this study and shows the distribution of MEC production capacity as well. The curve on the graph represents cumulative production capacity of all the MEC producing deposits included in the study, ordered from those with the smallest annual production capacity to those with the largest. The dashed vertical lines divide the graph into quartiles of cumulative production capacity. The four pairs of bar charts that are superimposed on the capacity distribution show the average costs of production (either average variable costs or total costs at a 0-pct DCFROR) for deposits of each size category.

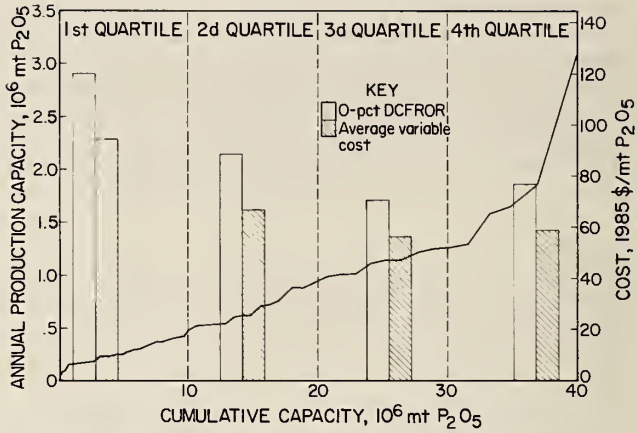

FIGURE 7. — Cumulative capacity of MEC producers, with average production cost by quartile, 1985.

There are 49 properties with capacities of about 0.5 million mt (P_2O_5 contained in phosphate rock) or less, which in total make up the first 25 pct of production capacity shown on the graph (i.e., the first quartile). The average costs of production for these (smallest) properties are the highest of any of the quartile averages, whether measured by the 0-pct DCFROR total cost level or by the average variable cost level. The 15-pct DCFROR total cost measure (not shown on this graphic) follows the same pattern as the 0-pct DCFROR. The average of the average variable costs for properties with 0.5 million mt of annual capacity or less is almost \$95/mt of P_2O_5 contained in phosphate rock. At a 0-pct DCFROR level, the average total cost of production is \$120/mt.

The second quartile contains 15 properties with annual production capacities between 0.5 and 0.9 million mt contained P_2O_5. The average total cost of production (0-pct DCFROR) for these properties is almost \$90/mt, and the average of the average variable costs for properties in this size range is \$67/mt.

The third quartile is comprised of eight properties ranging in size from 0.9 million to almost 1.3 million mt annual capacity. The average total costs for properties of this size are about \$70/mt and the average of the average variable costs are \$56/mt. The fourth quartile is comprised of six properties ranging in size up to more than 3.0 million mt annual capacity. Average costs of production for properties in this quartile are almost the same as for properties in the third quartile, \$76/mt on a total cost (0-pct DCFROR) basis, and \$59/mt for average variable costs.

These values suggest there are enormous economy-of-scale cost advantages. The fact that southeast U.S. properties are generally larger helps explain why U.S. operating costs are currently among the lowest in the world. Conversely, the generally smaller size of properties in many countries such as Egypt corresponds to a generally higher estimated cost of production from those deposits.

The following sections present a more detailed breakdown of the estimated capital, operating, and transportation costs of MEC deposits. Cost estimates are presented for both producers and nonproducers. Country-by-country values are shown for most of the categories of cost in terms of dollars per metric ton of phosphate rock. Some analysis is provided for several of the components that make up operating costs; these costs are shown in dollars per metric ton of P_2O_5 contained in phosphate rock.

Table 6.—Average capital costs[1] to develop nonproducing surface phosphate mines in selected countries

Country	Tonnage, 10^3 mt/yr		Cost,[2] 10^6 Jan. 1985 $				Cost,[2] Jan. 1985 $/mt (annual)	
	Ore	Product	Exploration, acquisition, development	Mine	Mill	Total	Ore	Product
Australia	5,700	2,400	4.6	21.3	31.4	57.3	10.10	23.90
Brazil	2,600	500	5.2	4.2	20.3	29.7	11.40	59.40
Morocco	3,800	2,100	28.4	73.0	63.2	164.6	43.30	78.40
Tunisia	2,200	1,100	1.1	13.3	23.9	38.3	17.40	34.80
United States:								
Southeast	10,900	1,600	65.5	30.1	67.8	163.4	15.00	102.10
West	900	700	4.0	10.9	53.1	68.0	75.60	97.10

[1] Excludes infrastructure and reinvestment.
[2] Rounded.

Capital Costs

Table 6 shows the average capital costs required to develop nonproducing surface deposits as estimated for this report. These costs represent the costs to acquire, explore, develop, and equip a new minesite, along with constructing any mine and mill plants and buildings necessary. The table shows that in most cases the capital cost for the mill (plant and equipment) is the largest cost in developing a phosphate deposit (40 to 80 pct of total capital investment). Not shown on the table are infrastructure costs, which in countries like Australia or Brazil can be very large and can make the difference in a choice to develop or not develop. Also excluded from the table are the necessary reinvestments that occur periodically over a property's life.

The data in table 6 are for an average-size property in each of the reported regions. The United States has the highest average capital cost per metric ton of annual capacity, and Australia has the lowest. A principal reason for high costs in the Southeast United States is the large expenditure for exploration, acquisition, and development (primarily land acquisition). While Morocco shows a substantial expenditure in the same category, this consists largely of development costs. Since most operations outside the United States are government owned or government controlled, there is generally very little expenditure involved in acquiring a property prior to development.

The low-cost Australian deposits are located in relatively remote regions, and actual development of these properties would require several times the reported expenditure in order to construct the needed infractructure. The costs reported in the "Availability" section reflect all costs (including infractructure and reinvestment) entailed in getting a marketable product to a transshipment point.

Production Costs

Table 7 shows average production costs for selected surface and underground operations in selected regions. Figure 8 illustrates the costs for surface properties only. Mines and deposits in some regions were excluded to protect confidentiality.

Mine operating costs for producing surface mines average $7.80/mt of product. Costs for the most significant producing regions outside the United States (Morocco, Tunisia, Israel, Jordon, Senegal, and Togo) range from $7.20/mt to $9.50/mt, reflecting a similarity in mining methods and stripping ratios. The mine operating cost in the Southeast United States ($4.90/mt) is lower than that of other regions, primarily because of low stripping ratios. Average mine operating costs for deposits not yet developed in the Southeast United States are estimated to be significantly greater (more than double that of producers), primarily because of the increased depth of the ore zones and the greater stripping ratios in the "southern extension" deposits (the most significant nonproducing deposits in the Southeast United States), which result in more materials handling and greater lengths of transport.

Mill operating costs for producing surface mines average $11/mt. Costs for southeast U.S. producers are less than those for producers in Morocco, Tunisia, Israel, Jordan, Senegal, and Togo ($7.40/mt as compared with a range of $10.30 to $12.80). This is primarily because the ore in the Southeast United States mines has had a significant pebble fraction that requires little or no beneficiation. However, undeveloped deposits in the southern extension in Florida have a much smaller pebble fraction, if any, and may require additional beneficiation; therefore, the mill operating costs will be greater.

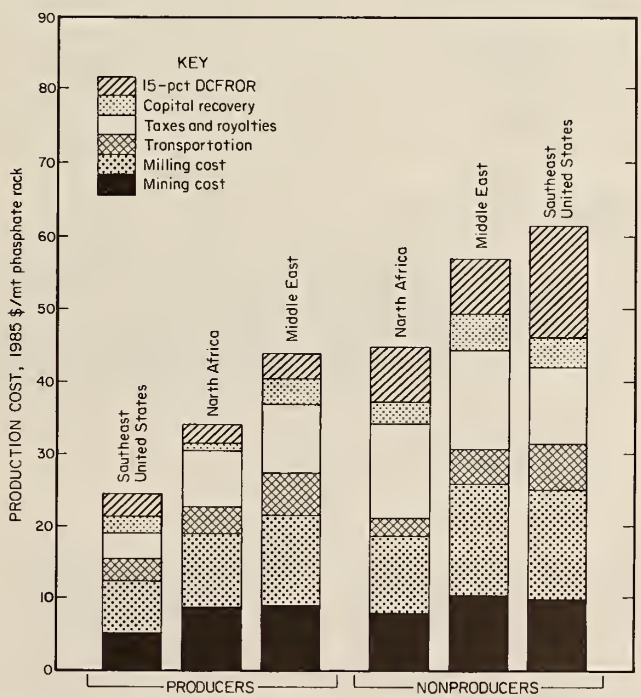

FIGURE 8. — Phosphate rock production costs for surface mines in selected regions.

Another reason the mine and mill operating costs are less in the Southeast United States may be the size of the operations. The average size of a producing mine in the Southeast United States is over 9 million mt/yr feed to the mill, while Morocco mines, e.g., produce under 6 million mt/yr feed (not including the large Daoui Mine). The data

Table 7.—Phosphate rock production costs for selected mines and deposits

(January 1985 dollars per metric ton phosphate rock)

Region and country	Operating costs				Recovery of capital[2]	0-pct DCFROR		15-pct DCFROR		
	Mine	Mill	Transport[1]	Net		Taxation[3]	Production cost[4]	Taxation[5]	Return on investment[6]	Production cost[7]
SURFACE OPERATIONS										
NORTH AMERICA										
United States:										
Southeast:[8]										
Producers	$4.90	$7.40	$3.00	$15.30	$2.20	$2.10	$19.60	$3.60	$3.20	$24.30
Nonproducers	10.00	15.40	6.10	31.50	4.00	3.10	38.60	10.90	15.40	61.80
West:										
Producers[9]	14.30	10.90	[10]	25.20	1.30	.90	27.40	1.50	1.50	29.50
Nonproducers[11]	20.20	14.70	12.10	47.00	5.10	1.60	53.70	8.70	13.70	74.50
SOUTH AMERICA										
Brazil, Peru, and Venezuela:										
Producers	6.00	15.60	6.70	28.30	4.60	4.70	37.60	10.70	9.40	53.00
Nonproducers	11.10	16.80	3.60	31.50	10.00	5.40	46.90	27.00	22.50	91.00
NORTH AFRICA										
Algeria and Tunisia:										
Producers	9.50	12.40	7.70	29.60	2.80	7.50	39.90	11.70	3.50	47.60
Nonproducers	4.70	12.90	3.60	21.20	2.60	8.10	31.90	15.30	8.00	47.10
Morocco and Western Sahara:										
Producers	8.60	10.30	3.60	22.50	.90	5.00	28.40	7.90	2.70	34.00
Nonproducers	7.90	10.90	2.30	21.10	1.60	5.90	28.60	13.30	8.90	44.90
WEST AFRICA										
Senegal and Togo: Producers	7.20	12.60	2.20	22.00	3.60	5.30	30.90	7.10	3.80	36.50
MIDDLE EAST										
Egypt, Israel, and Jordan:										
Producers	8.80	12.80	5.80	27.40	3.60	6.90	37.90	9.50	3.40	43.90
Nonproducers	10.50	15.70	4.50	30.70	4.90	8.60	44.20	13.90	7.70	57.20
Iraq and Syria: Producers	19.30	18.60	6.20	44.10	4.40	7.50	56.00	13.70	3.90	66.10
UNDERGROUND OPERATIONS										
NORTH AMERICA										
United States: Nonproducers[12]	$49.10	$36.00	$14.00	$99.10	$5.30	$2.10	$106.50	$14.20	$28.70	$147.30
NORTH AFRICA										
Morocco: Producers	18.50	17.30	4.30	40.10	.80	5.20	46.10	7.40	2.00	50.30
Tunisia: Producers	9.60	8.30	6.90	24.80	5.70	7.20	37.70	10.40	3.60	44.50
MIDDLE EAST										
Egypt: Producers	18.50	23.50	1.20	43.20	7.10	5.30	55.60	10.50	11.20	72.00
OCEANIA										
Australia: Nonproducers	8.60	14.90	14.10	37.60	8.30	2.20	48.10	7.00	6.60	59.50
Christmas Island[13] and Nauru:										
Producers	6.40	7.30	0.00	13.70	2.20	8.20	24.10	9.00	1.50	26.40

[1] Transportation costs to ports or acid plants that have been assumed as product destination points for this study. See table D-1 in appendix D.
[2] Includes cost of recovering remaining undepreciated investments in exploration, acquisition, development, mine and mill plant and equipment, and infrastructure, and reinvestments required over the life of the operation.
[3] Includes property, State, Federal, and severance taxes, and royalties where applicable, calculated at a 0-pct DCFROR.
[4] Equal to the sum of net operating costs, taxation, and capital recovery determined at a 0-pct DCFROR.
[5] Includes property, State, Federal, and severance taxes, and royalties where applicable, calculated at a 15-pct DCFROR.
[6] The per metric ton revenue increase necessary to obtain a 15-pct DCFROR.
[7] Equal to net operating costs, plus taxation generated at a 15-pct DCFROR, plus capital recovery, plus return on investment.
[8] Includes Florida and North Carolina.
[9] Represents only Idaho.
[10] Transportation costs for Idaho included in mill costs.
[11] Includes Idaho, Utah, and Wyoming.
[12] Includes Montana, Utah, and Wyoming.
[13] Australian territory.

represented in figure 7 show the degree to which economies of scale show up in averaged cost data. Though many factors are important in the determination of cost of production, the large size of mines in the Southeast United States may lead to an economy-of-scale advantage over many other operations worldwide.

Production costs are also shown for producing underground mines and deposits in north Africa and the Middle East and the nonproducers in the western United States (Utah and Wyoming). When these costs are compared with those of surface mines, it is apparent, as would be expected, that the underground operations are much more expensive to operate.

The underground nonproducers in the Western United States (Utah and Wyoming) would have average production costs higher than those of any other phosphate deposits evaluated. This is largely due to characteristics of the ore, coupled with the high costs of underground mining. Few of these highly uneconomical deposits are likely to be developed in the near future.

Transportation costs from mine to plant or port are relatively high where deposits are in remote locations, such as in the Western United States, where the phosphate rock often must be transported some distance for beneficiation, and in Australia, where the deposits are in the middle of Queensland and the rock must be transported to the coast.

The columns in table 7 labeled "Taxation" also include royalty payments, where applicable. Taxation costs are generally greater for nonproducers, because they are based on a phosphate price high enough to generate the

prespecified (15- or 0-pct) rate of return on investment. Since the revenue (and taxable income) necessary to cover the high overall costs (including profit) are greater in most cases for nonproducers, these properties will consequently have higher tax payments as well.

Figures 9 and 10 show distributions of the costs of labor and energy inputs for each of the MEC producers. The properties are ordered on the graph from those having the lowest average labor (or energy) cost per unit of P_2O_5 production capacity to those with the highest average per-unit cost. The dashed vertical lines divide the graph into quartiles, so that 25 pct of MEC production capacity with the lowest average labor (or energy) cost is shown between 0 and 10 million mt P_2O_5. Average costs for mines in several important regions have been located on the graph as well. Note that the average (and median) costs are not for the average (or median) property, but are instead for the average (and median) metric ton of cumulative capacity.

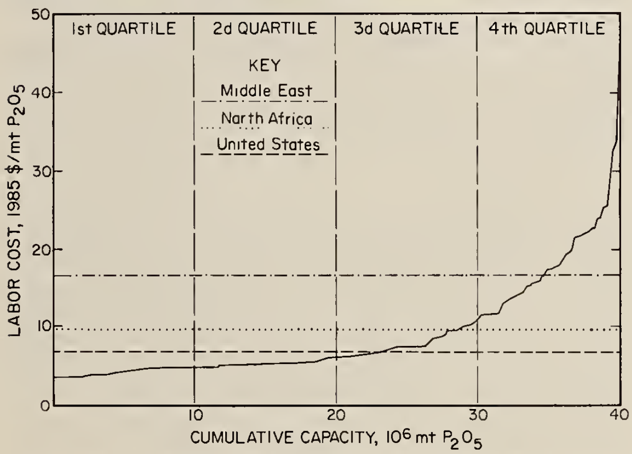

FIGURE 9. — MEC phosphate production costs, labor component, 1985.

Labor and energy are two of the more significant operating cost components of a phosphate rock mining and beneficiation operation. The levels of labor and energy costs reflect both the per-unit (of labor and energy) costs that exist in each of the producing MEC's, as well as the degree to which the component is utilized in the operation (factor intensity).

The average cost for labor for all MEC developed production capacity is just over \$9/mt P_2O_5 (approximately 16 pct of total operating costs), and the median (50th percentile of cumulative production capacity) is \$6/mt. The average labor cost in the United States is about \$7/mt P_2O_5, which is lower than the average labor costs at both north African and Middle Eastern phosphate rock facilities. Average U.S. labor costs are relatively low primarily because of the high degree of mechanization at U.S. properties. The high average for Middle Eastern producers is partly a result of the labor-intensive nature of the Egyptian operations.

The average cost for energy for all MEC developed production capacity is almost \$19/mt. This is a full third of the average total operating cost level. U.S. energy costs at currently producing properties are below the overall average and below both of the other regional averages shown, reflecting primarily the lower rates for available energy.

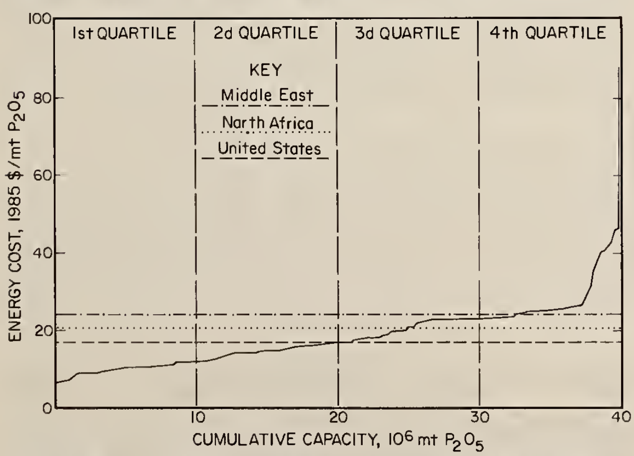

FIGURE 10. — MEC phosphate production costs, energy component, 1985.

Transportation Costs

The cost of transportation of phosphate rock and phosphate fertilizers is an important factor in determining the relative competitive position of alternative supplies. Phosphate resources and production capacity are widely distributed around the world, but the major consuming regions often are far from the producing areas. This has led to a large volume of international trade (as a percentage of production) and a substantial increase in the cost of delivered phosphate products relative to their cost of production (typical for bulk commodities).

The transport of phosphate products can be usefully considered as a combination of intracountry and intercountry movements. The intracountry portion includes movement of ore from mine to wash plant or mill (usually, but not always, in proximity), movement of phosphate rock from mill to port or phosphoric acid plant, and movement of phosphoric acid to port. Intercountry transport is mostly ocean shipment of phosphate rock, phosphoric acid, or phosphatic fertilizers from producer-country ports to consumers in other countries.

Figure 11 shows a distribution of intracountry transport costs for all MEC properties. These are the costs incurred by different producers in getting phosphate rock either to a port or to an in-country phosphoric acid plant and are included in the average variable costs reported in the "Availability" and "Supply" sections. Figure 11 does not include ocean transport of phosphate rock or any transport charges for phosphoric acid.

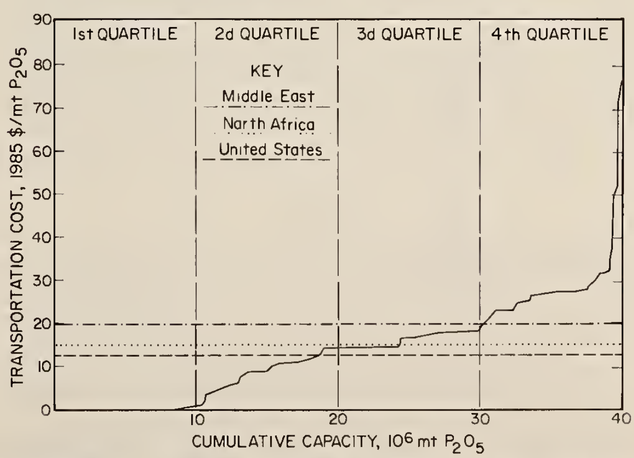

FIGURE 11. — MEC phosphate production costs, intracountry transportation component, 1985.

Properties accounting for almost 25 pct of the MEC annual production capacity show little or no transport costs. These are mostly mines that are located in proximity to a phosphoric acid plant or port. The average charge for intracountry transport of phosphate rock is \$14/mt P_2O_5 (contained in phosphate rock). This is 20 pct of the average operating cost (excluding royalty payments and severance taxes) and a smaller percentage of total costs. The U.S. average charge for in-country transportation is about \$13/mt of P_2O_5, slightly below the MEC average.

The estimated transport charge relates almost directly to the distance between mine and port, and where that distance is large the economic viability of the property can be in jeopardy. For example, the Duchess Mine in Australia is a former producer with estimated variable costs that place it in the middle of the range of producing properties, when transport charges are excluded. However, the Duchess Mine is 1,100 km from the port of Townsville, and the required cost of transporting phosphate rock this distance raises the production costs substantially.

The cost of transportation depends on the product being shipped, as well as the distance, size of load and vessel, and market conditions. That is, high-grade (i.e., higher P_2O_5 content) material can be shipped for approximately the same cost as low-grade material, and therefore, it is cheaper (measured as cost per unit of P_2O_5 content) to ship higher grade material. Some of the properties that produce higher grade phosphate rock are deposits in Finland, Nauru, Christmas Island, Togo, and Western Sahara. All these produce phosphate rock for export. (See table A-1 in appendix A for information on product grades at all MEC deposits.) Relatively lower grade material is produced in Egypt, Senegal, and Tunisia. Egypt's production is used primarily for local markets, since it is less competitive in the export market. Senegal exports phosphate rock, but analysis later in this report suggests there is incentive for Senegal to develop a phosphoric acid industry so it can export higher-value-added (and higher P_2O_5 content) material. Tunisia already is a major producer of processed phosphates and is able to reduce its transportation cost burden by shipping those higher grade products to export markets.

Acidulation Costs

The average variable cost for producing phosphoric acid from phosphate rock was estimated separately for each MEC facility included in the study (see appendix B for a listing of phosphoric acid plants included). This represents all costs incurred in producing merchant-grade phosphoric acid (55 pct P_2O_5), the most commonly traded concentration of phosphoric acid. Acidulation costs represent a large proportion of the delivered cost of phosphoric acid in each of the consuming regions represented in the network flow model. Figure 12 shows the phosphoric acid annual production capacity of each of the principal acid-producing MEC's. It also shows the average variable cost of production for all phosphoric acid plants in each of these countries. This average cost does not include the cost of phosphate rock.

The graph is drawn with cumulative capacity shown in order of increasing costs, by country. Two features of the graph stand out prominently. First, the United States has most of the MEC capacity, nearly 60 pct of the total. Second, the producers with the lowest costs are countries that have no domestic phosphate rock industry. Spain, the Republic of Korea, and Japan must import the phosphate rock required to produce phosphoric acid but are all able to compete in the export market because they have rela-

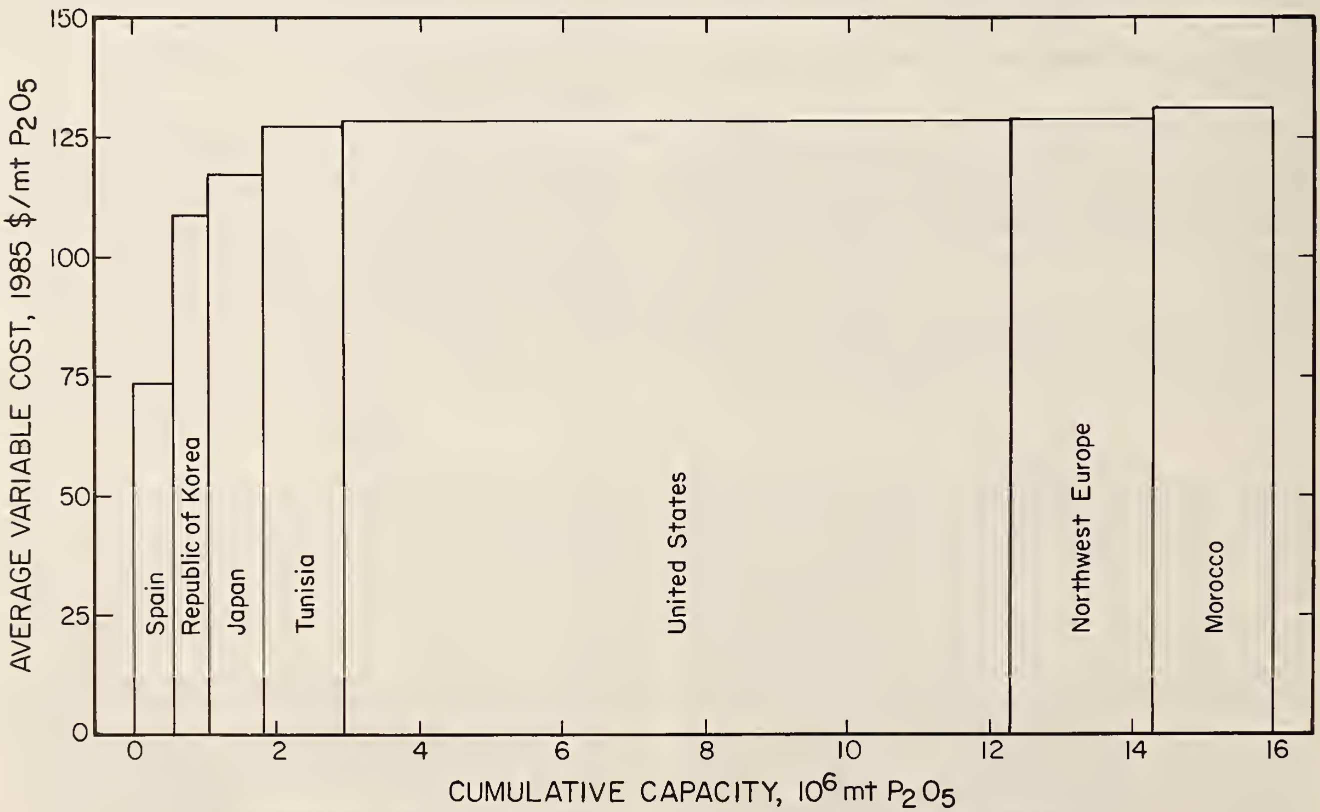

FIGURE 12. — Phosphoric acid production capacity and average cost, by region.

tively low costs of production. Each of these countries has a relatively low-cost source of sulfur, the major cost factor in producing phosphoric acid when the cost of phosphate rock is excluded.

The average variable cost in Western Europe (excluding Spain) is at the upper end of the cost distribution, similar to the levels for Tunisia, the United States, and Morocco. In addition, European phosphoric acid plants have to import nearly all the phosphate rock they process. The degree to which these plants can remain competitive in the future will depend on their ability to negotiate favorable contracts for phosphate rock and sulfur.

PHOSPHATE EVALUATION RESULTS

AVAILABILITY

Total

Approximately 35.1 billion mt of phosphate rock (demonstrated resource level) is potentially recoverable from the 206 mines and deposits in MEC's evaluated for this study. Morocco and Western Sahara (21.6 billion mt) account for 59 pct of the total, and the United States (6.1 billion mt) accounts for 17 pct.

The potential availability of phosphate rock from the MEC deposits analyzed is shown in figure 13. The tonnages shown include output from developing and explored deposits as well as from properties that are already developed and producing. No reference is made to the timeframe required to produce these quantities or the time required to develop different operations.

Approximately 33.0 billion mt of phosphate rock is potentially recoverable at total production costs (assuming a 15-pct DCFROR) less than $100/mt, from 176 mines and deposits. Approximately 1.3 billion mt of that total is potentially recoverable at costs ranging up to $30/mt (82 pct from the United States); 11.3 billion mt at costs ranging up to $40 (13 pct from the United States); and 14.2 billion mt at costs up to $50 (13 pct from the United States). An additional 2.1 billion mt could potentially be produced at costs over $100/mt from 30 deposits not shown on the curve.

The curve for north Africa includes potential production from Algeria, Morocco, Tunisia, and Western Sahara. Approximately 22.1 billion mt of phosphate rock (98 pct from Morocco and Western Sahara) is potentially recoverable from the 24 north African mines and deposits evaluated, 60 pct of the MEC total. Almost 7 billion mt is potentially recoverable at costs ranging up to $40/mt, and 9 billion mt is potentially recoverable at costs up to $50/mt.

The curve for the United States shows 4.7 billion mt of phosphate rock potentially recoverable from 98 mines and deposits at total costs ranging up to $100/mt. Nearly 1.1 billion mt of phosphate rock is potentially recoverable at costs ranging up to $30/mt; 1.4 billion mt at costs up to $40; and 1.8 billion mt at costs up to $50/mt. Another 1.4 billion mt that is potentially recoverable from 26 deposits (mostly in Wyoming and Utah) at costs greater than $100/mt is not shown on the curve.

The curve for the Middle East illustrates potential production of 1.9 billion mt at costs ranging up to $100/mt from 17 mines and deposits in Egypt, Iraq, Israel, Jordan, Saudi Arabia, Syria, and Turkey. An additional 238 million mt of potential production from one deposit is not shown on the curve because its estimated cost of production is over $100/mt. Potential recoverable phosphate from the Middle East amounts to 6 pct of the MEC total.

The three regions highlighted in figure 13 (the United States, north Africa, and the Middle East) account for 86 pct of the MEC recoverable demonstrated resources of phosphate rock. Other countries or regions included in the total availability for MEC's but not shown on separate curves are Canada, Mexico, South America, Oceania (which includes Australia and Nauru), Finland, India, Pakistan, Sri Lanka, Angola, Senegal, the Republic of South Africa, Togo, Uganda, and Zimbabwe. South America has an estimated production potential of 802 million mt of phosphate rock from 14 mines and deposits, in Brazil (11 mines and deposits) and Peru, Colombia, and Venezuela (1 deposit each). Oceania has an estimated production potential of 625 million mt from six mines and deposits in Australia (including Christmas Island) and one mine in Nauru. The combined potential tonnage from Senegal and Togo (two mines and deposits each), the Republic of South Africa, Angola, Uganda, and Zimbabwe (one mine each) amounts to 2.8 billion mt. The remaining 179 million mt is from Finland, India, Pakistan, and Sri Lanka (one mine or deposit each).

Total availability of potentially recoverable phosphate rock from producing mines is compared with that from developing mines and explored deposits in figure 14. The curves include only those mines and deposits with total costs of $100/mt or less. Of the 35.1 billion mt of phosphate rock estimated to be potentially available from MEC's, 33.0 billion mt (94 pct) is available at costs less than $100/mt, 40 pct from producing mines and 60 pct from undeveloped deposits. The 6.9 billion mt of recoverable phosphate rock potentially available from producing mines in north Africa accounts for 31 pct of their total potential of 22.1 billion mt. For the United States, out of a total of 4.7 billion mt of phosphate rock, 1.6 billion mt is from producing mines (34 pct). Of the 1.9 billion mt of phosphate rock potentially available from the Middle Eastern mines and deposits, 1.3 billion is from producing mines (68 pct).

The total availability of phosphate rock from all MEC mines and deposits, with a 0- or 15-pct DCFROR, is illustrated in figure 15. The illustration includes all mines and deposits with total costs of $100/mt or less, which at a 15-pct DCFROR have a total of 33.0 billion mt available. Approximately 22.2 billion mt of phosphate rock is potentially recoverable at costs ranging up to $30/mt at 0-pct DCFROR, while only 1.3 billion mt is available at the same cost level at a 15-pct DCFROR. This emphasizes that the economic viability of most of the MEC phosphate mines and deposits is directly related to the required rate of return as perceived by the property owners.

Annual

Another way of illustrating phosphate availability is to disaggregate the total resource availability curve and show potential availability on an annual basis. This method provides information on maximum production capacities available in the near future at currently producing properties and illustrates the lead times required before new production capacity can be added.

The annual availability curves reflect the installed annual capacity at proposed or already-developed operations. The curves thus represent a maximum attainable output

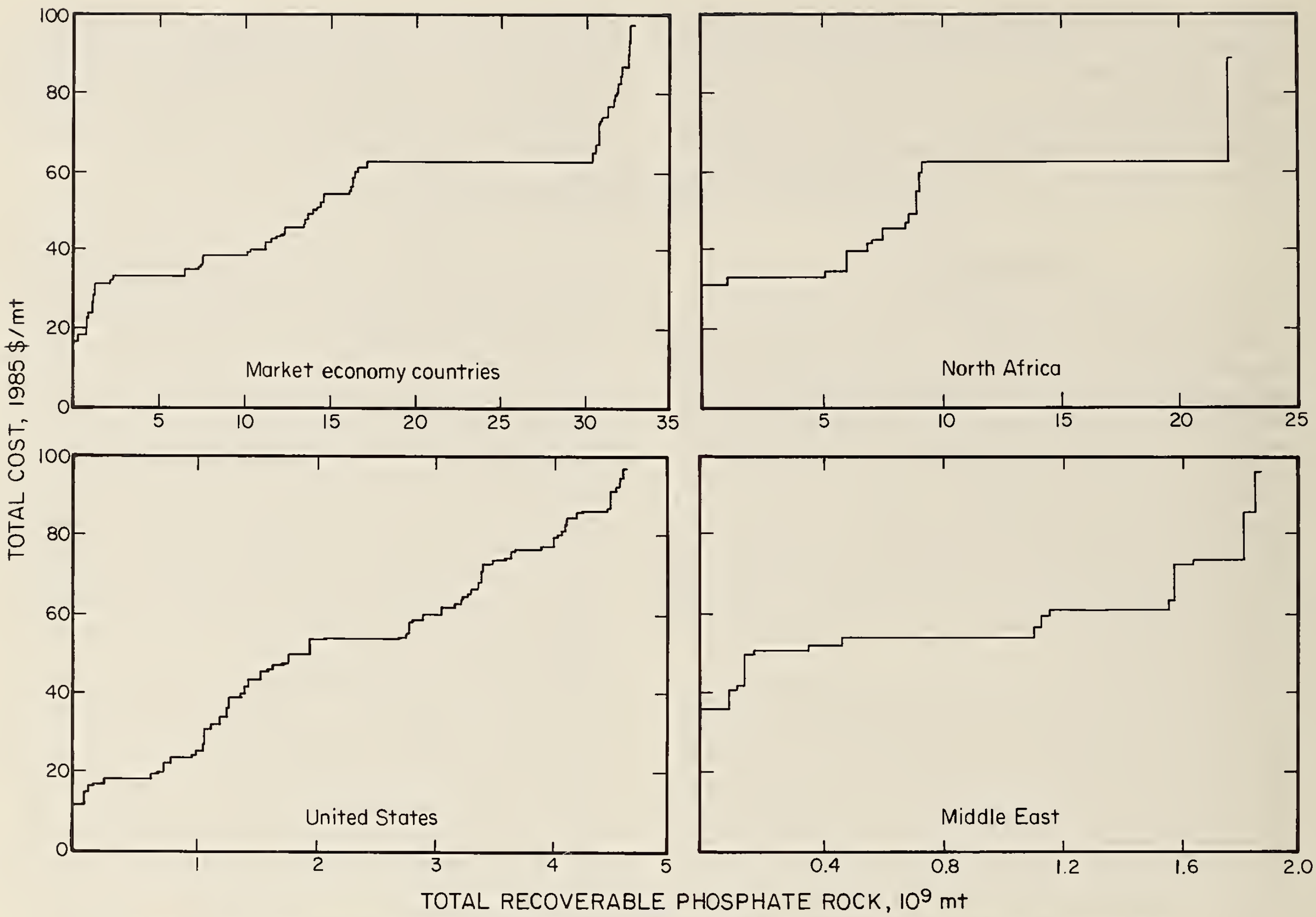

FIGURE 13. — Phosphate rock potentially recoverable from MEC mines and deposits (15-pct DCFROR).

each year, assuming that all operations produce at full capacity. The decline in output levels shown for later years is a result of resource depletion at several deposits, again assuming that production (and resource depletion) occurs at capacity levels for all years and that there are no additions to the resource base represented on the illustrations.

Separate annual availability curves have been constructed for producing and proposed operations. Annual availability is shown for producing mines in all MEC's and the following MEC regions: north Africa, the United States, and the Middle East. For undeveloped deposits, only one MEC curve was constructed. In order to show the maximum potential output from these deposits, development at all undeveloped deposits is presumed to begin in the same year (labeled "N"). The annual capacity (and cost) levels shown in the curve therefore reflect minimum required development times.

Potential annual production of phosphate from MEC producing mines from 1985 to 2000 is shown in figure 16. The curves reflect the production capacity of existing mines, including publicly announced planned expansions when known. The curves shown in figure 16 (note that each curve is constructed at a different scale) illustrate that maximum potential production from producing mines in the United States could decline dramatically in the near future. The U.S. phosphate industry has been producing at much less than full capacity in recent years, however, so the decline in potential U.S. production from currently installed capacity shown on the curve will actually be delayed for several more years and the eventual decline could be more gradual than shown. Maximum production capacity from north Africa, in contrast, will continue to increase through 1987, whether production is at full-capacity levels or not. Potential annual capacity in north Africa could decrease between 1987 and 1993, but additional capacity expansions are scheduled after 1993.

Table 8 shows the estimated annual production capacities, at different cost levels, at already-developed properties for each producing country in 1987 and 1997. The production capacities at each cost level are the actual data used to construct the annual curves shown in figure 16. As shown in table 8, the estimated capacity for all mines in MEC's in 1987 is 139.8 million mt of phosphate rock at average total production costs ranging up to $75/mt (including a 15-pct DCFROR). This compares with actual production of 106.4 million mt of phosphate rock in 1985 (*8*), indicating a 76-pct MEC capacity utilization at 1985 production levels. The estimated capacity for the United States in 1987 of 67.1 million mt is significantly higher than 1985 production of 50.8 million mt, a capacity utilization of about 75 pct.

Although not reported in the 1987 table, an additional 1.3 million mt of phosphate rock could be produced from currently installed capacity at two mines with production costs over $75/mt.

Table 8 also shows potential production of 107.6 million

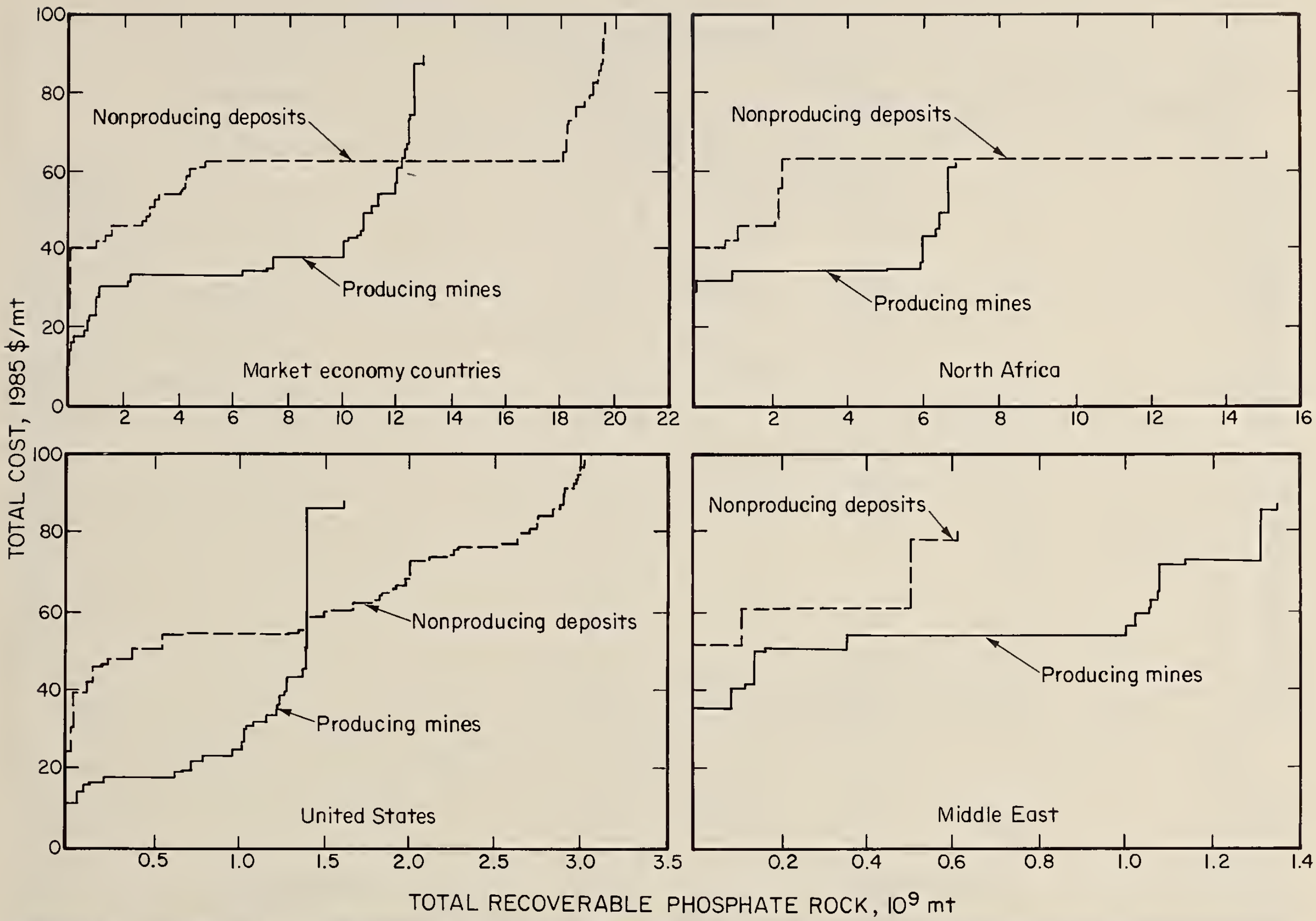

FIGURE 14. — Phosphate rock potentially recoverable from MEC producing mines and nonproducing deposits (15-pct DCFROR).

mt of phosphate rock (from already-developed properties) in 1997 at production costs ranging up to $75/mt. This number represents a minimum, as depletion at some properties will likely occur at a lesser rate than full-capacity production levels each year. An interesting comparison shown on table 8 is the relative decline in potential production capacity at currently producing properties in the United States and Morocco and Western Sahara. The United States shows a decline from 67.1 million mt in 1987 to 40.7 million mt in 1997, as the demonstrated resources of several producing mines become exhausted. Morocco and Western Sahara, on the other hand, show a minor decrease, from 30.2 million in 1987 to 27.7 million mt in 1997. This reflects exhaustion of resources at two deposits in Morocco, partially balanced by capacity expansions at three other currently producing operations.

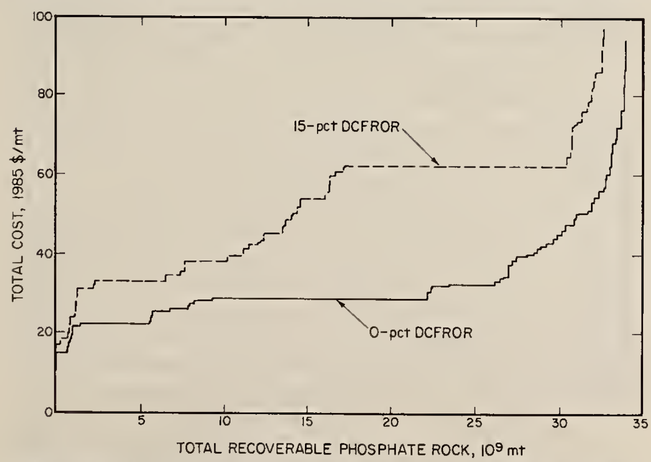

FIGURE 15. — Total MEC phosphate rock availability at 0- and 15-pct DCFROR.

Potential production of phosphate rock in 1997 (from properties that are already in production as of January 1985) at costs under $30/mt could decline to 32.2 million mt, compared with 64.1 million mt available in 1987. The U.S. share of this potential 1997 production capacity with costs under $30/mt would amount to 93 pct, while the Morocco and Western Saharan share would be zero. Of the 44.8 million mt of phosphate that could be produced in 1997 (from mines already in production in January 1985) at costs between $30/mt and $40/mt, however, the United States would account for only 17 pct and Morocco and Western Sahara would account for 50 pct. At estimated production costs between $40 and $50, a minimum of 16.1 million mt of phosphate rock could be produced in 1997, with the United States accounting for 19 pct and Morocco having 10 pct of the potential production in this cost range.

Some of the estimated decline of production capacity at producing mines in the United States would be delayed because of likely production at levels below full capacity. There could also be expansion of production capacities at

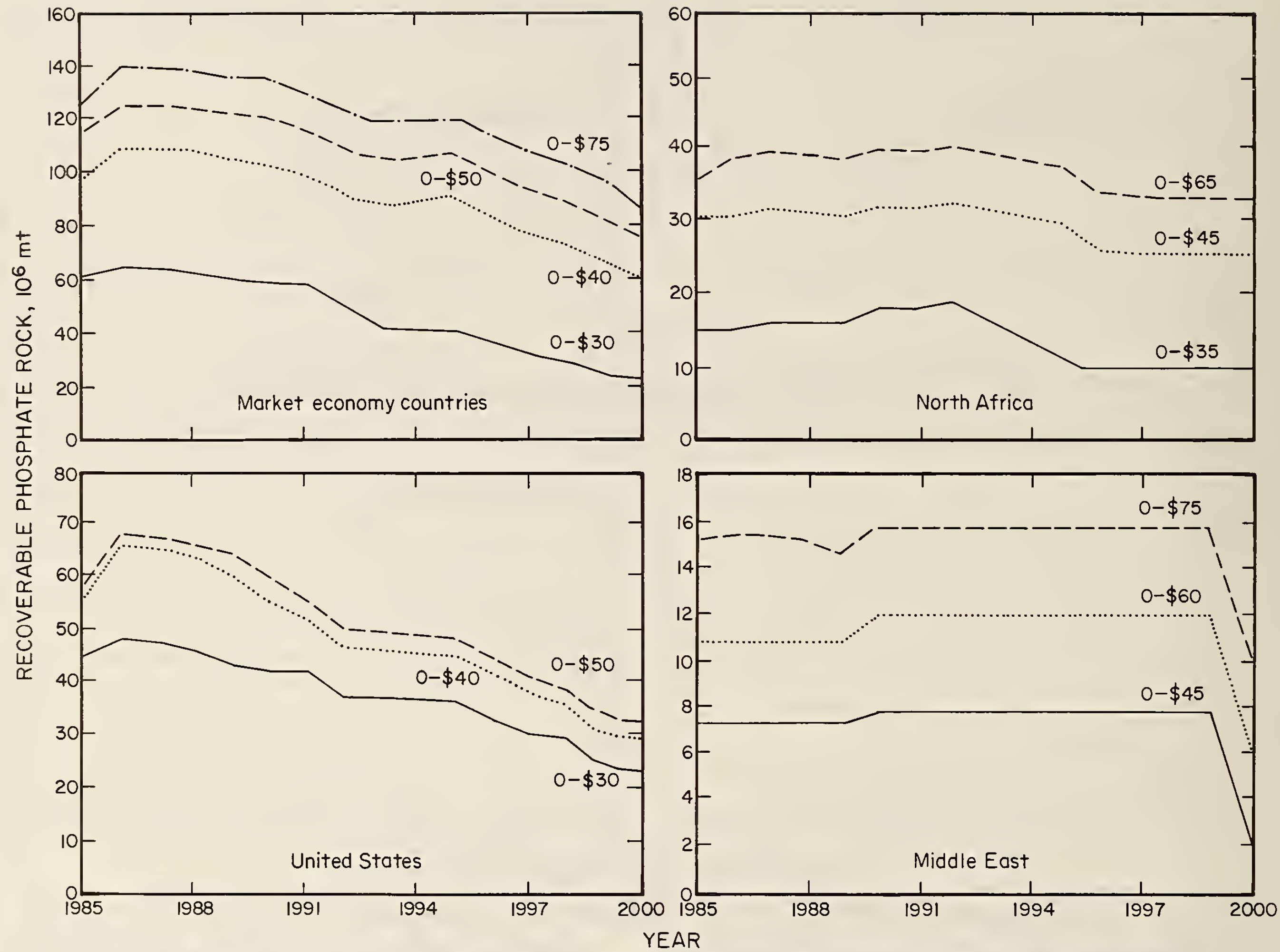

FIGURE 16. — Potential annual production from MEC producing mines at various cost levels (15-pct DCFROR).

some of the remaining producers that have large resources, although such expansions would effectively shorten producing lives. If the United States is to maintain current levels of production capacity, it will likely have to be through the development of new mines, which in most cases will have higher total costs.

The potential annual availability curves for all of the undeveloped MEC deposits included in the study are shown in figure 17. The annual curves for undeveloped deposits reflect the minimum required lead times before production can begin and show the potential production costs and potential annual capacities of the mines of the future. In these curves, all undeveloped deposits (with the exception of the mines that are currently under development) are assumed to begin preproduction development at the same time (a base year N). Consequently, the tonnage available in a given year is the maximum possible and unlikely to be realized since not all of the nonproducers will begin preproduction simultaneously. Mines that are already developing appear in the first couple of years, and then potential annual production increases dramatically as the other nonproducers begin to come on-stream in the year N+4 and beyond.

A key factor that this curve highlights is the tonnage differential at the different total cost levels. For this analysis, it is assumed that all of the nonproducing deposits begin preproduction development in year N, and all properties would be producing at full capacity by the year N+10 (although some capacity expansions would continue to occur beyond that time). In this case, 118 million mt of phosphate rock could be produced in the year N+10 at production costs ranging up to $100/mt (an additional 30 million mt at estimated production costs greater than $100 is not shown on the curve). Of this amount, 2.5 million mt could be produced at costs under $35/mt: 80 pct from the United States

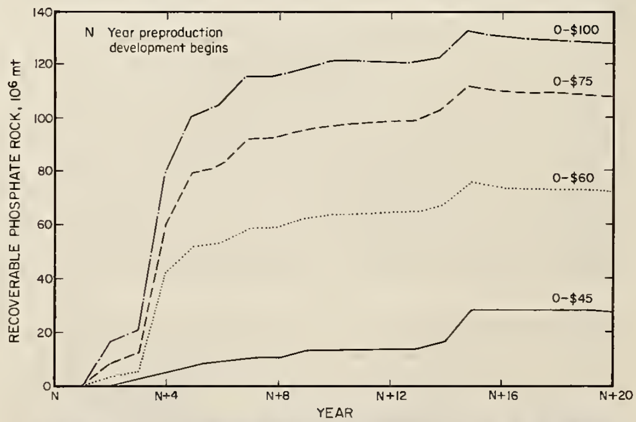

FIGURE 17. — Potential annual production from MEC developing mines and explored deposits at various cost levels (15-pct DCFROR).

Table 8.—Estimated potential annual production capacities for currently producing MEC mines, by country

(Thousand metric tons of phosphate rock)

Region and country	Cost, $/mt					Total
	$11.50 to $30	$30 to $40	$40 to $50	$50 to $60	$60 to $75	
1987						
North America:						
Mexico	—	800	—	—	—	800
United States	47,400	17,400	2,300	—	—	67,100
South America: Brazil	—	200	500	600	2,300	3,600
North Africa:						
Algeria	—	—	2,000	—	—	2,000
Morocco and Western Sahara	10,000	15,000	1,600	—	3,600	30,200
Tunisia	—	1,700	4,900	—	—	6,600
Other African countries:						
Senegal	—	600	1,500	—	—	2,100
South Africa, Republic of	—	3,200	—	—	—	3,200
Togo	3,200	—	—	—	—	3,200
Zimbabwe	—	—	—	—	200	200
Middle East:						
Egypt	—	—	—	100	1,200	1,300
Iraq	—	—	—	—	1,700	1,700
Israel	—	—	2,500	500	—	3,000
Jordan	—	5,700	1,100	—	—	6,800
Syria	—	—	—	800	1,600	2,400
Turkey	—	—	—	100	—	100
Oceania:						
Australia	1,500	—	—	—	—	1,500
Nauru	2,000	—	—	—	—	2,000
Asia: India	—	—	—	1,500	—	1,500
Europe: Finland	—	—	—	—	500	500
Total	64,100	44,600	16,400	3,600	11,100	139,800
1997						
North America:						
Mexico	—	800	—	—	—	800
United States	30,000	7,700	3,000	—	—	40,700
South America: Brazil	—	2,000	500	600	3,100	6,200
North Africa:						
Algeria	—	—	2,000	—	—	2,000
Morocco and Western Sahara	—	22,500	1,600	—	3,600	27,700
Tunisia	—	—	3,400	—	—	3,400
Other African countries:						
Senegal	—	600	1,500	—	—	2,100
South Africa, Republic of	—	5,500	—	—	—	5,500
Togo	2,200	—	—	—	—	2,200
Middle East:						
Egypt	—	—	—	100	1,200	1,300
Iraq	—	—	—	—	1,700	1,700
Israel	—	—	3,000	500	—	3,500
Jordan	—	5,700	1,100	—	—	6,800
Syria	—	—	—	800	800	1,600
Turkey	—	—	—	800	—	800
Asia: India	—	—	—	800	—	800
Europe: Finland	—	—	—	—	500	500
Total	32,200	44,800	16,100	3,600	10,900	107,600

NOTE.—Dashes indicate no production capacity within cost range.

and none from Morocco. At production costs between $35/mt and $40/mt, 6.2 million mt of phosphate rock could be produced: 44 pct from the United States, 32 pct from Morocco, and 24 pct from Togo. From $40/mt to $50/mt, 18.9 million mt of phosphate rock could be produced: 60 pct from the United States, 24 pct from Morocco, and 15 pct from Tunisia. At total production costs between $50/mt and $75/mt, an additional 67.7 million mt of phosphate could be produced, with 72 pct coming from the United States, 18 pct from Australia, 3 pct from Jordan, 3 pct from Israel, 2 pct from Tunisia, and 2 pct from Brazil. Of the 22.7 million mt that could be produced at costs ranging from $75/mt to $100/mt, 78 pct would be from the United States, mainly from deposits in the West.

The data underlying figure 17 are shown in table 9. The United States is predominant in the potential production of phosphate rock at costs under $50. Potential U.S. production in the year N+10 at $50/mt or less is 16 million mt, which is 58 pct of the total for all MEC's at that cost level.

Based on the data presented in table 8, it appears the United States will have to invest in expansions and/or the development of new mines within the next few years in order to maintain or increase current production. In order to achieve production at the nearly full-capacity 1981 level of 54 million mt, 25 pct of production in 1997 would come from mines that have yet to be developed.

Much of the potential tonnage shown in figure 17 for the year N+10 will not be required to meet future demand for a very long time. However, the U.S. phosphate industry in Florida will have to begin investing in the next few years to develop new deposits if it intends to maintain or expand upon current production levels. Over 70 pct of the phosphate from new mines in the United States that could be produced

Table 9.—Estimated potential annual production capacities for nonproducing deposits at average total production costs less than $100 per metric ton phosphate rock, by country, year N + 10

(Thousand metric tons)

Region and country	Cost, $/mt					Total
	$0 to $35	$35 to $40	$40 to $50	$50 to $75	$75 to $100	
North America:						
Canada	400	—	—	—	—	400
Mexico	—	—	—	—	1,200	1,200
United States	2,000	2,700	11,300	48,600	17,800	82,400
South America:						
Brazil	—	—	—	1,400	500	1,900
Colombia	—	—	—	—	100	100
Venezuela	—	—	—	—	400	400
North Africa:						
Morocco	—	2,000	4,500	—	—	6,500
Tunisia	—	—	2,900	1,500	—	4,400
Other African countries:						
Angola	—	—	—	200	—	200
Togo	—	1,500	—	—	—	1,500
Uganda	100	—	—	—	—	100
Middle East:						
Israel	—	—	—	2,000	—	2,000
Jordan	—	—	—	2,000	—	2,000
Saudi Arabia	—	—	—	—	2,500	2,500
Oceania: Australia	—	—	200	12,000	—	12,200
Asia: Pakistan	—	—	—	—	200	200
Total	2,500	6,200	18,900	67,700	22,700	118,000

NOTE.—Dashes indicate no production capacity within cost range.

for under $50/mt would cost in the $40 to $50 range, whereas most phosphate rock in Morocco from existing mines can be produced for under $40/mt.

There are numerous factors, however, that could enhance the outlook for phosphate availability from the United States, particularly over the long run. In addition to the demonstrated resources evaluated in this study for the United States, an estimated 7 billion mt of potentially recoverable phosphate rock exists at the inferred level (over 80 pct is in the Southeast), and over 24 billion mt of potentially recoverable phosphate rock exists at the hypothetical resource level (over 60 pct in the Southeast).[6]

New deposits will likely be discovered (particularly offshore deposits along the eastern seaboard); low-grade material could become economic to mine and beneficiate; or technological advances could enable the processing of high magnesium oxide material or the mining of deep deposits by the borehole mining technique. Any of these factors could greatly increase the amount of phosphate available in the future, both within and outside the United States.

Of immediate interest to the U.S. phosphate industry is more than 2 billion mt of recoverable phosphate rock in Florida at the identified resource level that contains high magnesium oxide material and is presently considered unacceptable by the industry owing to the higher beneficiation costs of producing an acceptable phosphoric acid plant feed. Given the progress several phosphate companies and the Bureau have made in developing beneficiation technologies to lower the grade of magnesium oxide in the phosphate rock product, this additional 2 billion mt of phosphate rock could become available in the near future, but at a higher cost.

[6] See appendix D for definition of resource classification terms.

SUPPLY

An economic model functions as a framework of analysis, which provides a measure against which to observe the real world. In its systemization, a model provides a consistent, reproducible audit trail from problem statement to conclusion. This being the case, even recognizably wrong conclusions benefit the analyses; results that are not intuitively appealing to the expert analyst must lead to the reevaluation of assumptions on which an analysis is based. Information learned from such reevaluation leads to refined understanding of the functioning of the minerals industry system, which after all is a more fundamental objective of the modeling effort than the solution of a limited number of specific problems. Absent the model, no such basis for improving understanding exists.

Toward this end, a three-part analytical framework has been developed, consisting of data analysis tools and two complementary economic models. The first application of these models to mineral market analysis is in the phosphate industry. The two perspectives provided are an aggregate outlook for the market in the medium to long term (market balance model), and a detailed, single-year analysis of the relative competitive positions of different suppliers of phosphate rock and phosphoric acid into each of the major consuming regions (network flow model).

Current Market Analysis

Model simulations for the 1981-85 period were used to examine the current markets for phosphate rock and phosphoric acid. Results from each of the models suggest that the least cost criteria (i.e., production coming from properties that have the lowest costs) lead to a reasonably accurate estimate of the allocation of production by region and that world trade flows can also be closely replicated based on least cost criteria. Solution values for "price" in the

market balance model simulation and "delivered cost" in the network flow model provide further evidence of the difficult financial position of many of the major producers, particularly in the United States. The model results also suggest reasons for the current production levels and trade patterns.

Historical Period Simulation Results

Table 10 shows the supply-side results of a historical period simulation using the market balance model. Quantities identified as "Actual value" are those taken from the 1984 Minerals Yearbook (MY) (*7*) and the 1986 Mineral Commodity Summaries (MCS) (*20*). These reported values are shown for each of the years 1981-85, along with simulated values for each of those years and the percentage difference between the two values. Production for CPEC's was not modeled.

The percentage differences between simulated and reported production levels are very small for almost all the principal producing MEC's for all the years. This indicates that the hierarchy of estimated cost levels for MEC deposits is adequate and that a simple competitive model is a responsible assumption about market behavior. It is also apparent that the Bureau's deposit data base shows more than sufficient production capacity to account for the reported output levels in every year for every major MEC.

A discussion of some of the larger differences in table 10 will highlight several features of the model. As an example, Jordan was expanding production capacity in the early 1980's. The market balance model depends on estimates of rated production capacity. However, rated capacity may be larger than actual production in the early years of a development or expansion because of the logistical difficulty of bringing everything together in an efficient continuous operation.

As a second example, the "Other MEC's" category, representing a mix of smaller producing countries, shows larger percentage differences than the major producers. This is because many of the smaller producers service a local market and enjoy a cost advantage in that market (which cannot be easily represented in the market balance model). A principal example of this is Brazil, with several deposits that seemingly have higher costs than other producing deposits. Brazil's large local market is able to absorb all local production; therefore, in model simulation, Brazilian deposits are all specified with minimum production levels so that their higher cost levels do not result in simulated property shutdowns.

The values for "Total world" production show differences of 2 to 4 pct in each year. There are two reasons why the value is nonzero. First is the "lumpiness" problem: i.e., properties are either producing at full capacity or presumed shut down. Many of these properties are large enough to make up more than 1 pct of the market. The second reason for nonzero differences in the total relates to the convergence criteria for price. If several properties have cost levels that are very close together, then the simulation effectively treats those properties as a unit and in successive iterations they will be simulated as producing or shut down in a block, compounding the lumpiness problem just described.

Table 11 reports the "prices" resulting from simulation and illustrates that these values must be interpreted with care. The price level solved for during a simulation equals the average variable cost of the producer with the highest cost. As such, it might be interpreted as a likely minimum price in a competitive market. The numbers in table 11 reinforce that idea. The solution (simulated) values for price in 1981 and 1982 are substantially below the actual (reported average) values. This indicates that most producers able to sell their product were getting a reasonable margin over operating costs. In 1983 and 1984, however, the higher cost producers were probably only barely covering those costs, and in 1985 the highest cost producers may even have been

Table 10.—Estimated[1] and reported[2] MEC production, 1981-85

(Thousand metric tons of P_2O_5)

Country	1981 Actual value	1981 Model result	1981 Difference, pct	1982 Actual value	1982 Model result	1982 Difference, pct	1983 Actual value	1983 Model result	1983 Difference, pct
Israel	624	670	+7	698	695	0	892	849	−5
Jordan	1,379	1,603	+16	1,427	1,521	+7	1,548	1,795	+16
Morocco	5,958	6,075	+2	5,700	6,266	+10	6,400	6,686	+4
Tunisia	1,287	1,416	+10	1,213	1,145	−6	1,700	1,750	+3
United States	16,365	15,642	−4	11,504	12,284	+7	13,088	13,650	+4
Other MEC's	5,730	6,686	+17	6,070	5,634	−7	5,995	6,557	+9
Total MEC's[3]	31,343	32,094	+2	26,612	27,548	+3	29,623	31,288	+6
Total CPEC's[4]	11,620	11,620	0	12,080	12,080	0	12,380	12,380	0
Total world	42,963	43,714	+2	38,692	39,628	+2	42,003	43,668	+4

Country	1984 Actual value	1984 Model result	1984 Difference, pct	1985 Actual value	1985 Model result	1985 Difference, pct	Average absolute difference, pct
Israel	995	875	−12	1,050	881	−14	7
Jordan	2,042	2,059	+1	2,282	2,075	−9	10
Morocco	6,762	6,968	+3	7,307	7,650	+5	5
Tunisia	1,554	1,806	+16	1,744	1,819	+4	8
United States	14,889	15,173	+2	15,435	16,745	+8	5
Other MEC's	5,940	6,832	+15	7,206	6,893	−4	10
Total MEC's[3]	32,182	33,716	+5	35,024	36,067	+3	4
Total CPEC's[4]	12,960	12,960	0	13,650	13,650	0	0
Total world	45,142	46,676	+3	48,674	49,717	+2	3

[1]Using the market balance model.
[2]Stowasser (*7, 20*).
[3]Data may not add to totals shown because of independent rounding.
[4]Not modeled.

losing money. The reported shutdowns in those latter years are evidence of the poor market being faced by producers worldwide.

Table 11.—Annual average price of phosphate rock, 1981-85

(Dollars per metric ton of phosphate rock)

Year	Reported nominal $[1]	Reported constant 1985 $[2]	Simulated constant 1985 $[3]
1981	26.63	28.33	21.73
1982	25.50	26.56	18.62
1983	23.97	24.59	24.02
1984	23.99	23.99	24.11
1985	23.50	23.50	25.42

[1]As reported f.o.b. mine basis in Stowasser (*20*).
[2]Nominal dollar value converted to Jan. 1985 dollars.
[3]Balance model simulation results.

Results from a network flow model simulation for the base year of 1984 reinforce the idea that high-cost producers may have been operating at a loss. Table 12 shows the production level results of the base year simulation. As with the market balance model, quantities identified as "Actual value" are taken from the MY (*7*). To the right of these values are listed the model results for each country or region and the percentage difference between the two. The weighted average difference in table 12 is calculated from weights based on actual production levels in 1984. At 5.2 pct, the overall error appears acceptable. Certain specific results, however, deserve consideration.

Table 12.—Estimated[1] and reported[2] MEC phosphate rock production in selected regions, 1984

(Thousand metric tons of P_2O_5)

Country	Actual value	Model result	Difference, pct
Israel	995	978	−1.7
Jordan	2,042	2,062	+1.0
Morocco	6,762	5,990	−11.4
Tunisia	1,554	1,235	−20.5
United States	14,889	14,490	−2.7
Other MEC's[3]	5,940	6,355	+7.0
Weighted average difference			5.2

[1]Network flow model simulation results.
[2]Stowasser (*7*).
[3]Other MEC's: Algeria, Brazil, Christmas Island, Egypt, Finland, India, Iraq, Mexico, Nauru, Senegal, Republic of South Africa, Syria, Togo, Zimbabwe.

The results from the model simulation showed Morocco producing 11.4 pct less P_2O_5 in 1984 than it reported having produced. These results would indicate that the relatively higher cost for mining, beneficiation, transportation, and acidulation of Moroccan phosphate materials was not a constraint on production and exports (as evidenced by the high reported values). Keep in mind that the network flow model attempts to fulfill demand from the lowest cost sources available systemwide.

One possible explanation for these results is that Morocco is attempting to capture unpriced social benefits of higher production levels. Morocco can send its lower quality phosphate rock to the state-owned Office Cherifien des Phosphates (OCP) phosphoric acid plants, reserving higher grade and/or quality phosphate rock for export as is. Once the lower quality phosphate rock is processed into phosphoric acid or phosphate fertilizers, its competitive disadvantage with regard to grade and/or quality is removed. To the degree that Morocco can market a greater level of total product in this manner without drastically affecting net profit, the country may be able to rationalize production on a basis of net social benefits. Other countries, including the United States, may also behave in this fashion given the proper incentives.

This concept is illustrated in figure 18, where the quantity of P_2O_5 produced (Q) is graphed against cost (C). Supply is assumed equal to the sum of the individual deposit marginal cost curves (at or above average variable cost) for all producers in any given country. D_0 represents the market demand curve for P_2O_5 faced by the producers and equals marginal private benefits (MPB). Equilibrium price and quantity are at C_0, Q_0. (These are normally sloped curves because of the laws of diminishing marginal utility and diminishing marginal returns.)

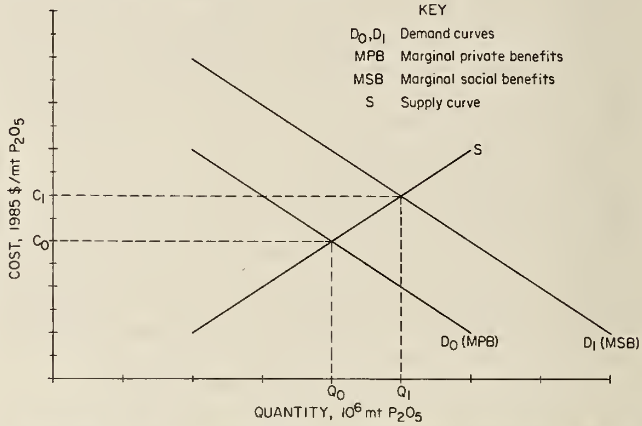

FIGURE 18. — Supply and demand incorporating social benefits.

Consider a scenario in which production of P_2O_5 generates positive externalities in the producing country, i.e., benefits not reflected in prices and therefore external to those prices. Demand curve D_1, which lies above D_0 by a distance equal to the external benefits, represents marginal social benefits (MSB). The new equilibrium is at C_1, Q_1.

This implies a higher rate of production than C_0, Q_0, the difference representing the increase in output necessary to capture the net social benefits of production. These benefits could include increased employment, foreign exchange earning, social stability, and enhanced opportunities for infrastructure development in remote regions. A strictly cost-based model, such as the network flow model, would not incorporate these nonprice issues into an optimal solution. The result would be underestimation of the level of production. This may be what happened in the base case simulation, since Morocco actually produced 11.4 pct more than the straight cost-based optimization suggests it would.

Similarly, the network flow model predicts that Tunisia would produce 20.5 pct less P_2O_5 in 1984 than was reported to have been produced. The marginal social benefits to Tunisia of increased production may well outweigh the costs. These costs might be absorbed as lower profit levels. It is interesting to note that Tunisia experienced low export levels prior to the development of the phosphoric acid and fertilizer complexes at Gabes and Sfax. Since that time, exports have increased markedly, perhaps indicating that (in select markets) Tunisia has been able to capture the value added to phosphate rock by acidulation.

It is frequently suggested that there is a move toward forward vertical integration in the phosphate industry, the development of secondary or final processing facilities so that firms or countries can capture the value-added profit from their primary resources. A country producing

phosphate may be relatively more competitive in international acid and fertilizer markets than in international phosphate rock markets, particularly if phosphoric acid is produced at or relatively near the phosphate mine and mill complex or if some ore is difficult to market because of poor quality. The results in the report suggest that in many instances this is, in fact, the case. Certainly it would appear to be so for Morocco and Tunisia.

Another example of the benefits of forward integration is suggested by a sensitivity analysis of the P_2O_5 industry of Senegal. This country anticipates producing approximately 700,000 mt of P_2O_5 by 1987. The network flow model predicts production of 655,000 mt of phosphate as rock as early as 1984, based on the relative competitiveness of phosphate rock in export markets. Even so, when the opportunity for increased domestic phosphoric acid production is introduced into the network flow model, the phosphate rock is directed to phosphoric acid plants and phosporic acid rather than phosphate rock is the product exported in the optimal solution. This would appear to support the suggestion that value-added benefits of producing phosphoric acid can be captured by phosphate-rock-producing countries if the opportunity (i.e., plant capacity) is available. Phosphoric acid produced near the mine will often be relatively more cost competitive than phosphoric acid produced at locations remote from the mine.

One possible explanation for the move toward producing higher value-added products is that freight costs in terms of dollars per metric ton of contained P_2O_5 are lower for phosphoric acid than they are for phosphate rock. Hence, it is more cost effective to ship phosphoric acid and other processed phosphate fertilizers. Many countries currently producing only phosphate rock perceive this opportunity, and as a result, more are moving or plan to move into phosphoric acid and fertilizer production.

Given that the market supply curve is equal to the horizontal summation of all individual supply curves, an increase in the number of acid and/or fertilizer producers will, by definition, shift the market supply curve away from the origin. Assuming that demand is elastic in the long run,[7] price will drop relative to what it would have been had new suppliers not come on-line. Economic profits currently earned in the phosphoric acid market could be competed away.

This does not bode well for high-cost phosphoric acid and fertilizer exporters. To the degree that market price is above a firm's average total cost (ATC), economic profits can be earned. However, if market price drops below the ATC, the firm will lose money. If this situation continues for a long enough period of time, high-cost producers will be forced out of the market. Conversely, firms capable of shifting their cost curves down (through increases in productivity or shifting of costs to other segments of the economy) would continue to be competitive in international markets characterized by decreasing relative price.

Results supporting the efficiency of forward integration are tempered by another very important factor, the cost of sulfuric acid. Sulfur represents approximately 80 pct of the non-phosphate-rock costs of merchant-grade phosphoric acid[8] in MEC's. Obviously, the cost of sulfur has an enormous impact on the relative competitive status of phosphoric acid producers. In fact, availability of low-cost sulfur appears to be almost as important as availability of low-cost phosphate rock in determining the competitive status of phosphoric acid output.

For example, the Republic of Korea, Japan, and Spain all import phosphate rock; none have phosphate reserves. Yet all are successful exporters of *value-added* phosphate products. The data suggest that relatively low-cost sulfur may be an important factor in this success. Spain has high-grade pyrite deposits located in the same geographic region as the phosphoric acid plants. The production capacity of the pyrite deposits is far in excess of the quantities of sulfur required by the phosphate industry. Spain also produces byproduct sulfur from metallurgical plants. Japan produces over 2 million mt of byproduct sulfur per year as well as importing sulfur as solid brimstone and sulfuric acid. Japan acts as an exporter of sulfur products. The Republic of Korea imports both elemental sulfur (native and byproduct) and sulfuric acid, with Canada (elemental) and Japan (elemental and sulfuric acid) as major suppliers.

Sulfur costs used in the network flow model for phosphoric acid plants in the Republic of Korea and Japan are 20 to 30 pct below those used for southeast U.S. and Moroccan phosphoric acid producers. Sulfur cost in Spain is less than half that in the United States or Morocco. Using these cost numbers, phosphoric acid produced and sold in Japan and the Republic of Korea appears to be competitive in Asian markets with phosphoric acid imported from the United States or Morocco. This is particularly true in those instances where Japan and the Republic of Korea use low-cost phosphate rock from Nauru or Christmas Island.

One inference that can be drawn from these results is that there are advantages to be gained from vertical integration. In those instances where a particularly low-cost sulfur source is available, there appear to be benefits to backward vertical integration—the development of processing facilities and the importation of a primary commodity to complement the natural advantages a country may have with regard to other inputs required for production of a final product.

Consider Spain as an example. The Spanish started extracting their pyrite deposits when Sicilian sulfur was depleted (1800's) and in the ensuing years have developed an extensive sulfur industry. The Bou Craa phosphate deposits in the Spanish (Western) Sahara were discovered by Spain in 1947 and were developed by Empresa National del Sahara, with production beginning in 1972. Phosphate rock was shipped to Huelva, Spain, a port near the Spanish pyrite deposits. The Spanish Sahara was taken over in 1975 by Morocco and Mauritania, but phosphates were so sensitive an issue politically that Morocco guaranteed the supply of raw phosphates to Spain. Morocco continues to ship phosphate rock to Huelva, 2.6 million mt of rock in 1984. Further, Spain is a major exporter of wet-process phosphoric acid, (93,400 mt contained P_2O_5 in 1984) and ammonium phosphates (48,400 mt contained P_2O_5 in 1984). This situation would appear to be an example of successful backward integration, even though the mine and benefication plants are no longer controlled by the Spanish.

Another apparent example of backward integration is the development of phosphoric acid and fertilizer facilities in Wyoming. Chevron Chemical Co. has built a large sour-gas plant at Rock Springs, WY, to scrub sour gas (remove the sulfur). As a result, Chevron has a continuous source of byproduct sulfur that is relatively low cost compared with Frasch sulfur, and which must be disposed of in some manner. Chevron has purchased the Vernal phosphate mine

[7] "Long run" is a conceptual period of time in which all inputs except technology are variable; i.e., the only fixed variable in the production function is technology.

[8] Calculated in terms of contained P_2O_5 in acid.

at Vernal, UT, built a slurry pipeline from Vernal to Rock Springs, and built acidulation facilities at Rock Springs. Chevron now produces, at a competitive cost, phosphoric acid and acid-based fertilizer products. Assuming that the original intention was to enhance the market value of natural gas rather than to provide a sulfur source, this would appear to be another instance of successful backward integration.

The network flow model predicts a higher level of production in "Other MEC's" than was reported to have occurred in 1984 (table 12). It has been suggested that many properties in remote regions produce for strictly local markets. To replicate this market scenario, the network was designed to allow mines in many "Other MEC's" to feed local markets with no transportation cost. Little cost information is available on intracountry distribution of phosphate products. While the assumption of no-cost distribution may be somewhat unrealistic, it is reasonable to assume that phosphate products produced locally are sold in local markets as well as exported.

The result of this design feature is a higher level of predicted phosphate production in countries serving local markets over no-cost distribution paths (zero-cost arcs). Mathematically, this occurs because low-cost paths will always be chosen over high-cost paths, and producers with the opportunity to ship over zero-cost arcs will be more likely to produce, other things being equal, than producers with costed transportation arcs.

Current Trade Patterns and Delivered Costs

A feasible set of trade flows can be derived from the solution to the network flow model. The model identifies the mines and mills from which phosphate flows into each of the fertilizer-consuming regions. The optimal solution to the network flow model can be fed into a transportation algorithm (described in appendix E). The output from this program is a set of feasible paths from mines to final demand regions (nodes), consistent with the flows allowed in the optimal cost-minimization solution. The cost of the most expensive path to a final demand node can be considered a proxy for marginal cost at that demand node. The marginal costs at each MEC phosphoric acid demand node are listed in table 13.

Table 13.—Estimated marginal costs of delivered phosphoric acid, by region, 1984 (constrained network model)

(January 1985 dollars per metric ton)

Demand region[1]	*Marginal cost of delivered acid product*
North America:	
Canada	$370
United States	366
South America	382
Africa	410
Western Europe	433
Asia	473

[1]Eastern Europe and U.S.S.R. acid demand not shown, as reliable cost data are unavailable.

Marginal cost of delivered phosphoric acid is similar throughout the Western Hemisphere, with U.S. and Canadian costs differing by less than 2 pct. The average of North American (U.S. and Canadian) costs, $368, differs from the South American delivered cost by less than 4 pct at the margin. Costs may be consistent as a result of available relatively high-quality deposits of phosphate ore in the United States and Brazil and the availability of sulfur in the United States, Canada, and Latin America.

Not surprisingly, delivered cost is higher in Western Europe than in the Western Hemisphere. This may result from the fact that the majority of phosphate rock used in acidulation is imported. The marginal cost for delivered phosphoric acid products in Africa is also higher than the price in the Western Hemisphere. This may result from two factors. First, little product appears to be imported to the African continent, based on International Fertilizer Industry Association (IFA) trade data (*14*). If this is the case, foreign suppliers with costs below those of the marginal supplier may have been excluded from the market. Second, African producers may be exporting their lower cost product to maximize foreign exchange earnings, leaving higher cost output to fulfill regional demand. In other words, some of the African product is high cost, but may be intended for local markets.

The highest marginal delivered cost for phosphoric acid products, according to the model, is in Asia. This is not an unreasonable result given the physical distance between east Asia and most exporters of phosphate rock and phosphoric acid (other than Japan and the Republic of Korea). The results from the transportation algorithm can also be presented as a graph of cumulative delivered product versus delivered cost. Each step on the curves in figure 19 corresponds to a unique path to a specific demand region. All of the paths to each demand region are shown in increasing cost order.

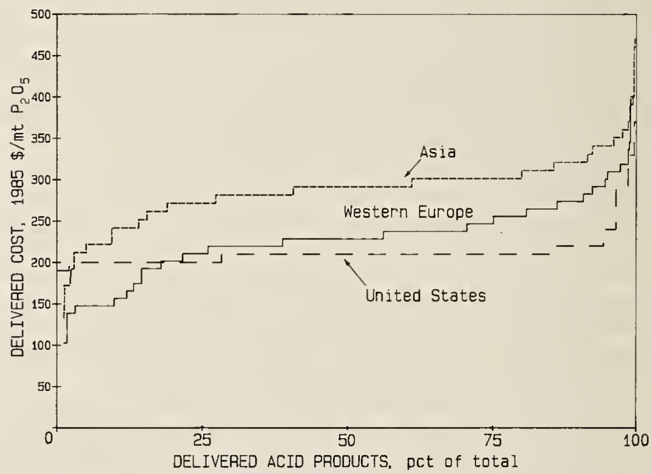

FIGURE 19. — Delivered cost of phosphoric acid to selected regions, 1984.

The position of the curves in figure 19 reinforce the conclusions drawn from the data on marginal costs presented in table 13. Phosphate products can be delivered at lower cost to U.S. consumers than they can be to either Western Europe or Asia, and they can be delivered at lower cost to Western Europe than to Asia. The median-cost suppliers of phosphoric acid products to Asia have costs higher than the median delivered costs to Western Europe or the United States. The existence of this broad, relatively flat, middle range (from 25 to 75 pct of delivered product) for all regions indicates that these markets have a large number of suppliers with similar levels of delivered cost and indicates relatively competitive markets. Even producers with the lowest delivered costs (the first quartile) do not appear to incur costs substantially below the median.

Natural Markets

The network flow model is useful in identifying the natural export markets for each supplier of phosphate rock and phosphoric acid. A natural export market is one in which the supplier has the capability to deliver the product at a cost below that of other potential suppliers. The base case of the phosphate network flow model incorporates numerous constraints that reflect current market conditions, such as known contracts or traditional trading patterns. To ascertain natural markets, all constraints other than capacities have been removed and the model reoptimized on a strictly cost-minimizing basis. The results do not necessarily reflect actual trading patterns but suggest those markets in which an exporter would be most competitive on a cost basis alone.

One of the interesting results of the simulation is that Tunisia appears to have natural markets for phosphoric acid rather than for phosphate rock. This is consistent with previously mentioned model results and Tunisia's recent moves toward adding more phosphoric acid capacity. This would appear to be true for the Republic of South Africa also. Results for Senegal and Morocco indicate they have natural markets for both products. Algeria, conversely, has no natural markets, which may be why Algerian exports flow mostly to CPEC markets, where free market forces are less important. Jordan's natural markets are for phosphate rock only, as are Israel's.

Natural markets for U.S. phosphate rock producers occur in Western Europe, Asia, Canada, and South America. Natural markets for U.S. phosphoric acid cover these same regions. U.S. producers appear to be competitive with other producers in most major markets in the world. To the degree that one or more competitors are willing to supply product below cost in certain export markets, however, U.S. producers (who must cover their costs to remain in business) will be at a disadvantage.

Supply Curves

World Phosphate Rock Supply

The market balance model solution is in terms of a worldwide balance for P_2O_5 contained in phosphate rock. The relevant supply curve is a step function that is an aggregation of individual deposit curves. It has as many steps as there are developed deposits (those capable of supplying phosphate rock to the market in the current time period). Each step is located at the level of a mine's average variable costs and has a horizontal distance equal to annual production capacity. Average variable costs include transportation to a port or to a phosphoric acid plant.

Figure 20 is a representation of the world phosphate rock supply curve for 1985. The steps are further aggregations of the deposit data so as to disguise individual company data. Almost 14 million mt is shown as available with no associated cost, representing supply available from CPEC deposits and small deposits not individually represented in the data base. The reported level of world consumption has been superimposed on the curve, as has the reported U.S. average price for phosphate rock. The costs for non-U.S. deposits have been adjusted to account for the historical average differences between the U.S. gulf coast price of phosphate rock and the Casablanca price of phosphate rock (see appendix E for a complete explanation).

The equilibrium price from the market balance model base case simulation is $82.15/mt of P_2O_5 in phosphate rock, slightly higher than the 1985 reported price. (This same value was reported earlier in table 11 in terms of dollars per metric ton of phosphate rock product.) The conclusion to be drawn from this is that some producers may be losing money on a cash- (average variable) cost basis.

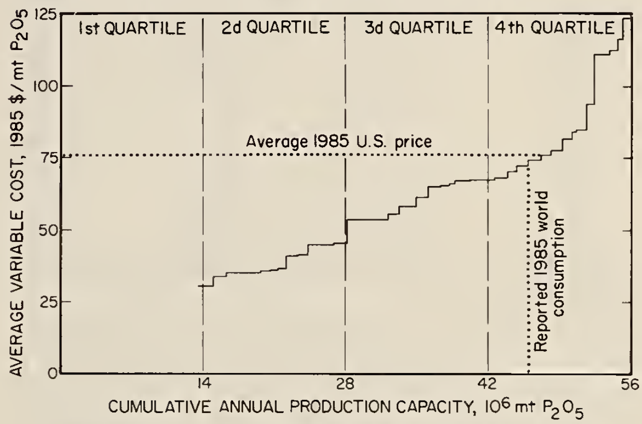

FIGURE 20. — World phosphate rock supply, 1985

Another conclusion that can be drawn from figure 20 is that there exists a lot of additional production capacity at only slightly higher costs. That is, moderate increases in demand can be met by increased production from deposits with costs similar to the current highest cost producing properties. Although the mechanics of actual price determination are far more complex than can be represented in the market balance model, the implication of these results is that price would not have to rise much to elicit more output from already-developed properties.

Results from a base case projection, presented in the next section, will address this same point. The pace of resource depletion at currently producing properties and development of new capacity at currently undeveloped properties will be highlighted for different projected rates of growth in demand. The cost levels at likely producing properties in each future year will suggest when and how much price will likely have to rise in order to cover average variable costs.

Regional Phosphoric Acid Supply

Supply curves for phosphoric acid in various regions can be derived from solutions of the network flow model. (See appendix E for an explanation of their derivation.) These curves show the amounts of phosphoric acid that can be delivered to a particular region at different levels of delivered cost. All quantities are in metric tons of P_2O_5 contained in phosphoric acid. This product represents demand for all fertilizer products (*21*).

Figures 21, 22, and 23 depict the phosphoric acid supply curves for the United States, Western Europe, and Asia for the base year of 1984. The general conclusion drawn from the worldwide supply curve for phosphate rock (fig. 20) is reinforced by the shape of these regional supply curves for fertilizers. Supply is relatively elastic. That is, moderate increases in demand in any of the regions can be satisfied with material from suppliers who have only slightly higher costs than the operations that are producing in the simulation.

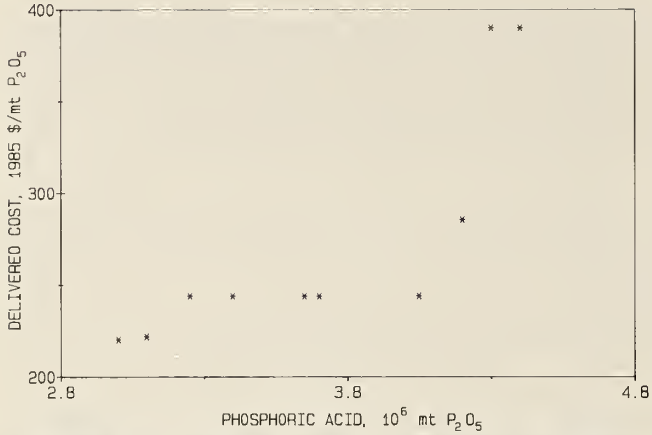

FIGURE 21. — Short-run supply of phosphoric acid, United States, 1984.

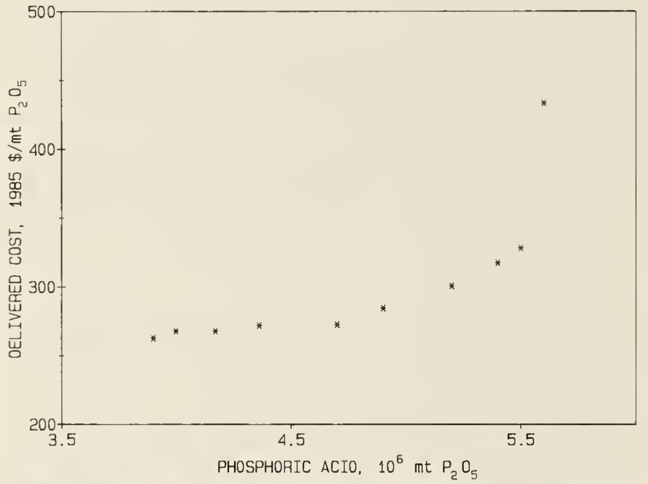

FIGURE 22. — Short-run supply of phosphoric acid, Western Europe, 1984.

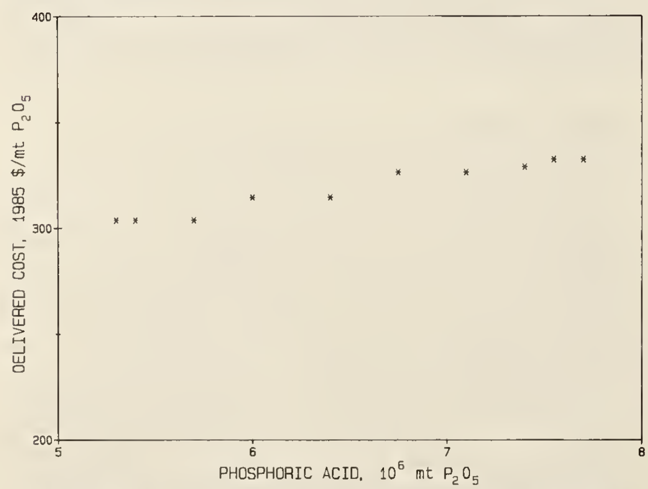

FIGURE 23. — Short-run supply of phosphoric acid, Asia, 1984.

These results indicate that it is not just phosphate rock production capacity that is in excess over current requirements. There is also an excess of phosphoric acid capacity. This situation means there is currently a competitive market in all regions, with a large number of potential suppliers vying for market shares. The near-term outlook for phosphate producers is not good either, with several of the major producing countries indicating a desire to expand phosphoric acid and fertilizer production facilities in an effort to capture the benefits from marketing higher-value-added products.

Projection Period Analyses

A base case simulation was performed with the market balance model for the period 1985-2000, incorporating the definitional supply curve and all of the supply-side logic discussed earlier, but using a predetermined constant-percentage increase in demand. Results for an intermediate year (1995) have been fed into the network flow model, and an analysis of the relative competitive positions of the likely suppliers in that year was performed also. Both sets of results are examined in this section.

Base Case Analysis to the Year 2000

Total world demand begins at the 1985 value reported in MCS (*20*) and grows at 3 pct/yr. This growth rate in demand was used in the base case projection because it results in annual world demand equal to approximately the low end of the range for the year 2000 projection contained in reference *11*, after converting that number to P_2O_5 content and accounting for processing and handling losses that are not already taken care of by the data development and availability methodologies.

The supply values in the simulation reflect production from demonstrated resources at properties that either have installed capacity or are likely to develop production capacity over that period. Production from CPEC's is presumed to grow at 3.2 pct/yr, a continuation of the trend observed over the past 10 yr. The supply total each year is forced by the model logic to be equal to demand each year (within the algorithm's convergence criteria), after adjustments for recoveries and P_2O_5 content.

Table 14 addresses the question of adequacy of supply over the entire forecast period from already-developed properties. It shows projected demand levels each year and the shortfall in supply that would occur if no new property development were to take place. The phosphate rock shortfalls presume all available properties can produce at capacity each year; downtime or closures at any property could

Table 14.—Adequacy of supply from current producers

(Thousand metric tons of P_2O_5)

Year	Demand[1] (3-pct/yr growth)	Phosphate rock shortfall	
		No expansion allowed	Announced expansion occurs
1985	49,663	0	0
1986	51,154	0	0
1987	52,688	0	0
1988	54,269	0	0
1989	55,897	0	0
1990	57,574	0	0
1991	59,301	2,751	0
1992	61,080	7,524	2,338
1993	62,912	11,930	5,797
1994	64,799	13,607	7,093
1995	66,744	14,986	7,476
1996	68,746	19,208	11,296
1997	70,808	22,906	15,248
1998	72,933	25,936	18,632
1999	75,120	29,330	22,043
2000	77,375	33,228	25,851

[1]Source for base year demand value: Stowasser (*11*).

make the shortfall larger. The shortfall numbers do not allow for adjustments in demand that would inevitably occur if a shortage of product actually happened but rather are meant to highlight growth in the market and depletion of resources over time and to indicate the need for expansions or new property development.

Column 2 in table 14 shows annual total world demand for phosphate rock under an assumption that demand grows at 3 pct/yr. This value has already been adjusted to account for processing and handling losses but assumes no change in inventory levels from the present. The third and fourth columns illustrate the supply shortfall that would occur if no new property development happens. Column 3 contains the values from the simulation in which no expansion is allowed at currently producing properties, in addition to no new development. Column 4 assumes that announced expansions at several properties (e.g., Meraa El Arech in Morocco, Patos de Minas in Brazil, and Palabora in the Republic of South Africa) occur, but no new properties developed.

Capacity at already-developed properties is sufficient to satisfy projected demand through the year 1990. By 1991, however, resource depletion and demand growth lead to a shortfall in production of 2.8 million mt of P_2O_5 in phosphate rock that must be made up from new property development or expansion at already-developed properties. The amount of the shortfall grows each year until, by the year 2000, about 33 million mt of P_2O_5 in phosphate rock have to be obtained from somewhere other than already-developed capacity at current producers.

If already-announced expansion plans are presumed to occur, the shortfall in supply would not begin until 1991, and in the year 2000 the shortfall is less but still almost 26 million mt. These values represent minimum amounts of new production capacity that must be developed if demand grows at 3 pct/yr, assuming planned expansions occur.

More than a third of the reduction in production capacity occurs in the United States. There are also a substantial number of Tunisian mines likely to deplete over that period. Morocco, Jordan, Togo, and Nauru would also lose production capacity if no new development or expansions were allowed.

The information in table 14 is similar to that presented earlier in the "Availability" section. With presumed full-capacity production from all currently developed properties, the annual availability curves (fig. 16) showed a decline in production capacity after only a few years. In table 14, the estimated demand level dictates the level of total production. Not all developed properties are producing at capacity, and therefore, the depletion of resources happens more slowly. In both cases, the shortfalls shown are not meant to imply that such shortfalls in supply will actually come to pass. Rather, they show the opportunity for expansions and development of new production capacity.

There will be no shortfall in supply as long as the orderly development of already-known deposits is allowed to occur. The base case simulation allows for that development. Table 15 shows the results of the base case simulation with regard to changes in production capacity on a year-by-year basis. Production capacity losses due to depletion of resources begin in 1987 and continue throughout the simulation period. New production capacity becomes available as early as 1986 (reflecting development already under way) and also continues throughout the period.

The earliest entry in table 15 is for expansions at currently producing properties, which begin in 1986 and end in 1995. There are 13 properties with "solid" expansion plans built into the deposit data base, some of them with expansion in more than one year. These have all been announced publicly and are deemed likely to occur in the indicated years (although no expansion is guaranteed). Not all announced expansion plans are presumed to occur, since many producing countries express their desires for increased market share without regard to whether there is financing available or a reasonably assured market for their product.

Table 15.—Simulated changes in MEC phosphate rock production capacity (1986-2000)

(Thousand metric tons of P_2O_5)

Year	Lost because of resource depletion	Added by expansions	Added by new property development
1986	0	1,288	0
1987	621	548	0
1988	1,241	275	1,068
1989	0	506	2,112
1990	1,362	1,112	2,193
1991	2,469	491	996
1992	3,201	605	3,139
1993	409	838	2,061
1994	0	1,138	96
1995	0	1,104	970
1996	3,705	0	2,307
1997	2,456	0	4,475
1998	1,031	0	1,941
1999	2,017	0	3,510
2000	2,028	0	2,734
Total	20,540	7,905	27,602

The expansions and developments reported in table 15 show the industry operating at less than full-capacity utilization; table 15, therefore, presents information somewhat different from that in table 14, which reported on additional capacity that would be absolutely required in order to meet projected demand. The MEC capacity utilization rate for 1985 is about 83 pct, and it rises (in the simulation) to greater than 95 pct by the year 2000.

The geographic distribution of production capacity over the forecast period stays similar to the present pattern (shown earlier in table 10). However, there are some anomalies. Jordan's demonstrated resource base and production capacity will have to be supplemented by additional exploration and development (over and above Esh-Shidiyah) around the year 2000. Preliminary indications are that resources exist, but it is too early to tell at what cost. The U.S. share of production begins to erode early in the 1990's because of resource depletion. The U.S. share picks up late in the 1990's because most of the rest of the world's lower cost demonstrated resources have already been developed by that time. The United States has a large amount of demonstrated resources, however, and represents the large bulk of properties developed in the last 3 yr of the simulation. It may well be that additional resources are proved up in foreign countries, depletion may be slower than indicated, and the U.S. industry would continue to decline as a percentage of the world's production capacity.

Table 15 showed that there are ample demonstrated resources in the MEC's to be developed. They are located in all the major producing countries (except Nauru). However, the cost of providing the necessary additional production capacity between now and the year 2000 is large. New property development required to satisfy demand growth at 3 pct/yr would cost more than $7 billion (1985 U.S. dollars). Nearly 70 pct of that total would be for mine and mill plant and equipment (fig. 24). The costs for expansions at already-developed properties are also large, more

than $1 billion, with almost 60 pct of the total being for mill expansions, and more than half the remainder for mine investments. Investment in downstream processing facilities is not included in the capital cost estimate.

These capital expenditure totals reflect an assumption that the lowest cost properties are the first to develop to fill the gap between projected supply and projected demand. There are some special cases. The Dagbati property in Togo, for example, is relatively low cost, but it is viewed as a replacement property and not allowed to develop until the early 1990's, just prior to the likely depletion date at the major currently producing deposit. Conversely, some higher cost properties could be developed in a few countries to serve local markets. Brazil and India, for example, are countries that desire to be self-sufficient in fertilizers and appear willing to pay a premium to achieve that goal.

The bar chart of figure 24 clearly shows several reasons why the U.S. producers may be at a disadvantage in the future. U.S. capital expenditures are projected to be very large for exploration, land acquisition, and mine preparation, particularly for land acquisition. The foreign properties will have to make sizable investments in infrastructure, but not nearly so much as to offset the land acquisition expenditures of the United States. The U.S. producers of the future may also need to make larger expenditures than their foreign competitors on mill plant and equipment, on average, reflecting the more complex mineralogy of the U.S. deposits. (The possibility for reduced capital expenditures exists at some properties in Florida that may slurry-pump mined ore significant distances to existing plants.)

On a per-unit basis, the likely new U.S. deposits will need an investment of more than $300/mt annual P_2O_5 capacity (equivalent to $93/mt annual phosphate rock capacity), while new foreign deposits will need only an average of $220/mt annual P_2O_5 capacity ($68/mt phosphate rock). By far the cheapest new capacity of the future will come from expansions at currently producing properties, where only $126/mt of annual P_2O_5 capacity ($40/mt phosphate rock) is likely to be required. A large portion of expenditures for expansions lies in the mill plant and equipment category.

Figure 25 shows average costs of production at the properties that are likely to be producing over the 1985-2000 period, presuming demand grows at a 3-pct annual rate and new properties are developed in a timely fashion. The three lines shown on the graph represent different measures of cost. Each of the lines corresponds to the highest cost by a producing mine in a particular year. The two dashed lines use cost measures equal to the DCFROR values at 0 and 15 pct, discussed earlier in the "Availability" section. They can be interpreted as indicators of a desired price, where the marginal property is getting a reasonable return on investment but the price is not high enough to entice new companies into the market. The desired price is one that a company (or government) might expect before it makes a development decision. The solid line is the average variable (marginal) cost at the highest cost producing property. It can be interpreted as a likely minimum price; i.e., if the price is lower than this value, the marginal property will not be earning sufficient revenues to cover cash operating

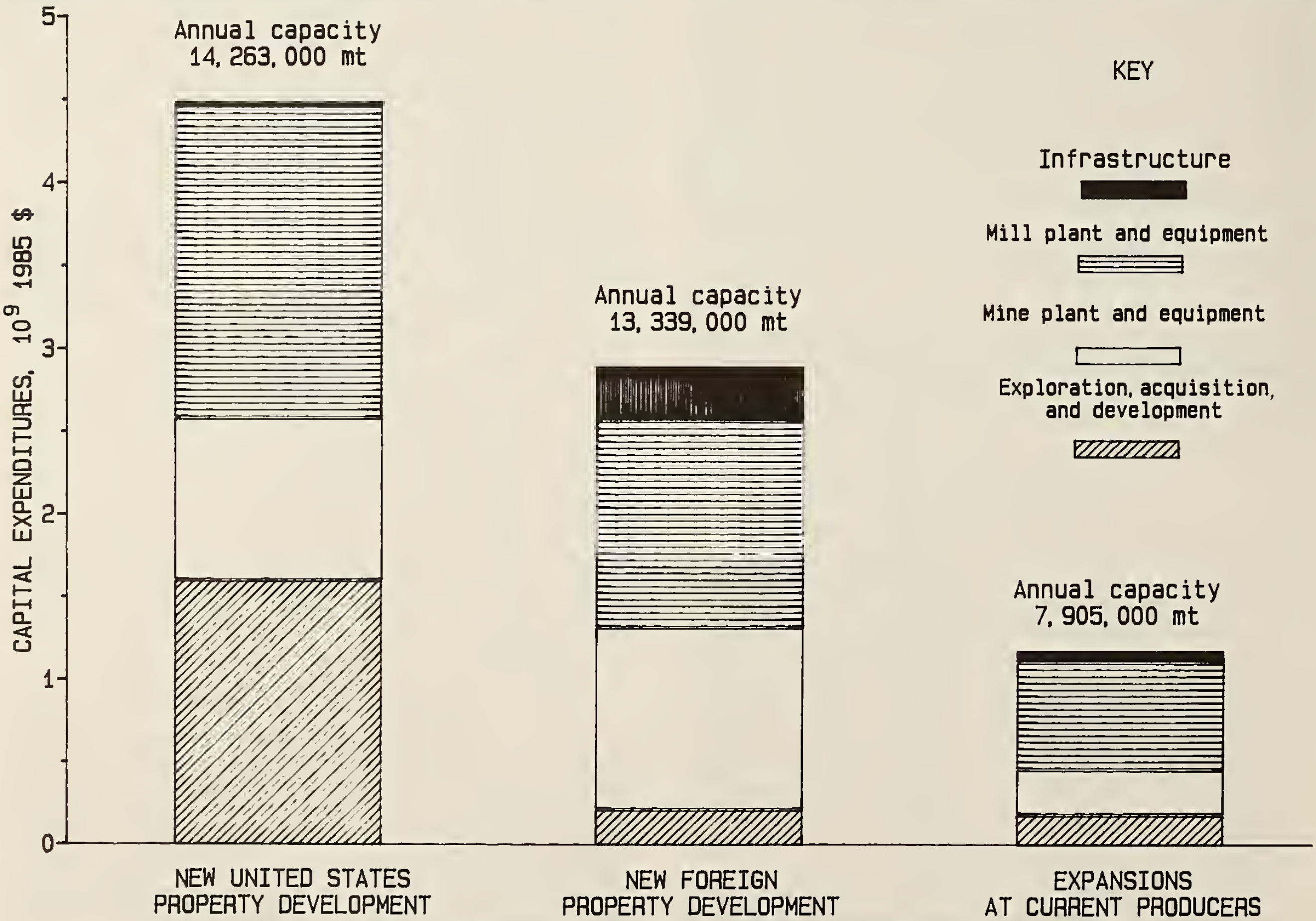

FIGURE 24. — Estimated capital expenditures for new production capacity (1985-2000).

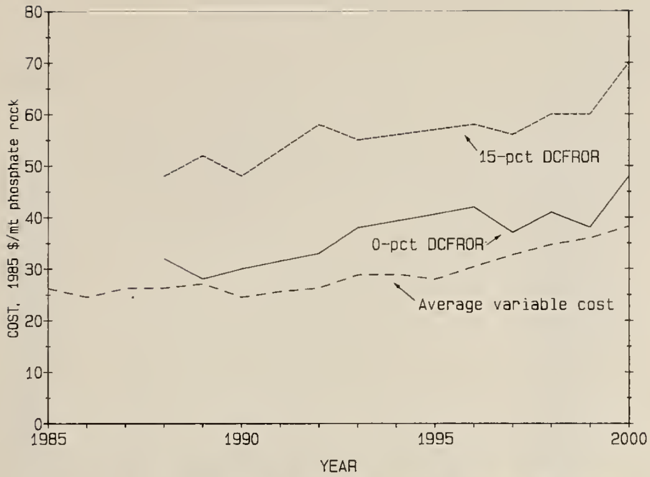

FIGURE 25. — Estimated average costs of marginal producing properties worldwide (1985-2000).

costs and might be better off to shut down.

Costs have been converted from a P_2O_5 content basis to a standardized 31 pct phosphate rock basis for easier comparison with numbers reported in other Bureau publications. The average variable cost (likely minimum price) shown in figure 25 starts at just over $25/mt of phosphate rock in 1985 and rises to $38/mt in 2000. These values represent a price for phosphate rock at a U.S. gulf port, and after accounting for transportation costs, the 1985 value is similar to that reported in MCS (*20*) as an f.o.b. mine price. Costs at foreign properties are converted to a U.S. gulf equivalent by using the historical relationship between the U.S. and Casablanca prices. The year 2000 value indicates that a 40- to 50-pct rise in price is necessary so that deposits with the capacity to produce in that year can earn sufficient revenues to cover their variable costs.

The 15-pct DCFROR line in figure 25 corresponds to the same measure reported in the "Availability" section of this report. This "incentive price" level might be considered a reasonable target price by a market-oriented firm choosing between alternative investment opportunities. The earliest of the new properties developed (in 1988, table 15) requires nearly $50/mt of phosphate rock to earn a 15-pct return on investment. Recent prices have been in the $23/mt to $27/mt range, close to the all-time low in real dollar terms. By the late 1990's, a typical new property will have an average total cost level (assuming a 15-pct DCFROR) of $60/mt and above.

The 0-pct DCFROR total cost measure is also shown for the same set of properties. This level might be more appropriate for a Government-owned operation, where benefits accrue in the form of increased domestic employment opportunities, larger export earnings, enhanced infrastructure for developing other sectors of the economy, or increased political stability.

The average total costs for new producers at the 0-pct DCFROR level are lower than at the 15-pct level. The first properties developed have average total costs around $30/mt. By the late 1990's, the 0-pct DCFROR cost is in the $40/mt to $45/mt range for newly developed properties.

With regard to who develops the new capacity, each of the major producing countries has additional resources to replace mines that are likely to deplete, the United States included. Most of the major producing countries also have sufficient resources to maintain their market share in a growing market, the United States included. However, not all resources are available at the same costs. It is here that the U.S. phosphate industry is at a disadvantage. Much of the domestic phosphate that is yet to be developed requires a higher price if investment is to earn a reasonable rate of return. Also, since most of the production capacity outside the United States is government owned, other potential new mine developers may be looking at a lower target rate of return when contemplating a decision to develop.

Competitive Position of Potential Suppliers in 1995

Results from the market balance model simulation for the period up to 1995 were fed into the network flow model so that the competitive position of potential suppliers in that year could be examined. Results from the market balance model showed that 12 properties would be closed because of resource depletion: Nauru, Christmas Island, and 5 each in the United States and Tunisia. Forty-six properties were designated as potential new producers: 24 in the United States, 6 in north Africa, 6 in South America, 3 in the Middle East, and 7 in various other countries. Demand for phosphoric acid in MEC's was increased by 3.4 million mt of contained phosphate, or 17 pct over the 1984 base year value.

All potential new properties were offered the opportunity to produce, but the network flow model predicted that only 17 would produce; i.e., given the predicted 1995 demand levels, only 17 of the new properties had variable delivered costs low enough to make them competitive with previously developed properties. Table 16 presents the comparison of actual production of P_2O_5 in MEC's in 1984 with predicted production for 1995, as well as the percentage change in production compared with the increase in worldwide demand for phosphoric acid. Several of the MEC producers could increase their production by amounts exceeding the increase in demand, which indicates that they could gain a bigger market share over their position in 1984. It is important when interpreting these numbers to note that a forecast for changes in production in China is excluded from the 1995 model. To the extent that production in China does increase by 1995, increases in shipments of phosphate to Asia from MEC deposits would be smaller and the percentage increase in production, especially for those countries whose natural markets include Asia, could be less.

The simulated increases in production in the United States and Morocco in 1995 are comparable in magnitude, indicating that both would retain their positions as major producers and exporters of phosphate products. Israel and Jordan could both gain market share, although not to the degree, in absolute terms, that the United States and Morocco could. Egypt, Syria, and Algeria could lose market share in relative and absolute terms because of high cost.

Table 16.—Estimated production in selected MEC's in 1995

(Thousand metric tons of P_2O_5)

Country	1984 production[1]	Predicted 1995 production	Production increase, pct	Pct of demand increase
Israel	995	2,261	127.2	37.7
Jordan	2,042	3,214	57.4	33.8
Morocco	6,762	9,885	46.2	114.4
Tunisia	1,554	1,812	16.6	16.9
United States	14,889	18,354	23.3	113.0
Other MEC's[2]	5,940	7,426	25.0	41.8

[1]Source: Stowasser (*20*).
[2]Other MEC's: Algeria, Brazil, Christmas Island, Egypt, Finland, India, Iraq, Mexico, Nauru, Senegal, Republic of South Africa, Syria, Togo, Zimbabwe.

Table 17.—Estimated marginal costs of delivered phosphoric acid, by region, 1984 and 1995 (unconstrained network models)

(January 1985 dollars per metric ton)

Demand region[1]	Marginal cost of delivered acid product	
	1984	1995
North America:		
Canada	$260	$268
United States	244	223
South America	258	258
Africa	250	249
Western Europe	300	299
Asia	326	323

[1]Eastern Europe and U.S.S.R. acid demand not shown, as reliable cost data are unavailable.

The marginal costs of delivered phosphoric acid in selected regions for 1984 and 1995 simulations are shown in table 17. These values are not directly comparable to those reported for 1984 in table 13 because these simulations did not include the constraints embodied in the 1984 base case, e.g., contractual obligations and established trading patterns.

The delivered costs are lower across the board in the unconstrained analysis, suggesting that there may be more economically efficient trading patterns than those observed in 1984. Nevertheless, the relationships between the marginal cost values by year are meaningful. The marginal delivered cost values are virtually the same in 1995 as in 1984. This is consistent with large, low- (variable) cost properties coming on-line and considerable excess capacity currently available. Figure 25 reiterates these findings; the average variable cost curve increases by negligible amounts prior to 1996. U.S. delivered costs decrease in 1995 because some low-cost material previously exported is now available for U.S. markets.

The cost relationships between regions are also of interest. Figure 26, showing the distribution of delivered phosphoric acid costs to major MEC regions, reinforces the information in table 17. Phosphoric acid products could be delivered to the United States at lower costs than to either Western Europe or Asia, and to Western Europe at lower costs than to Asia. One change from the results presented for 1984 (fig. 19) is the shape of the curves. Only the United States exhibits a broad middle range centered at 50 pct of delivered phosphoric acid product, where delivered costs are nearly constant. For Asia, the flat range is narrower and shifted up and to the right, centering closer to the 75-pct mark. For Western Europe, there is no flat range. The model suggests that by 1995 Asia and probably Western Europe will have fewer suppliers facing the median cost. These changes reflect the fact that increasing amounts of delivered phosphoric acid product in these regions could only be gained at continual increases in delivered phosphoric acid costs. Keep in mind that the 1995 simulation is based on a substantial increase in demand to be met from MEC production, implying that most of the phosphoric acid plants considered high cost in the 1984 simulation would need to be operating.

Natural markets in 1995 shift somewhat compared with those reported in the previous section for 1984. (Natural markets are those in which a supplier would appear to have a cost advantage relative to alternative suppliers.) The natural markets for phosphate rock from Togo expand to include some Far Eastern areas. The natural markets for Tunisia remain for phosphoric acid product only, but the area in which it competes effectively expands into the Far

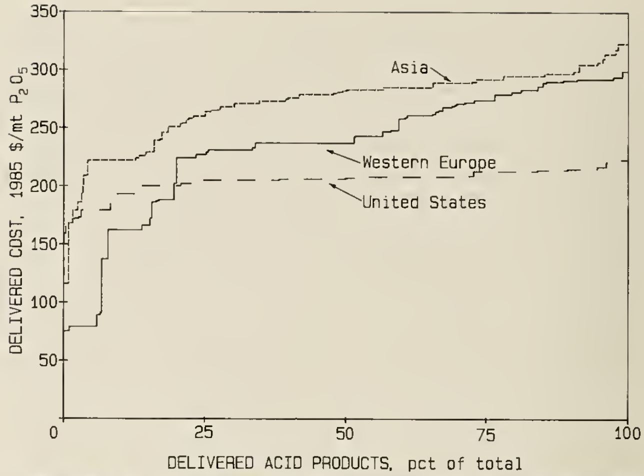

FIGURE 26. — Delivered cost of phosphoric acid to selected regions, 1995.

East. Morocco could lose some phosphate rock markets but gain phosphoric acid markets. Senegal's and Jordan's natural markets remain the same, while Israel appears to gain phosphate rock markets.

The United States continues to have natural markets for phosphate rock in Canada, Western Europe, South America, and Asia. The natural markets for phosphoric acid, however, could be limited to Canada, South America, and Asia. The ability of MEC producers to gain or maintain natural markets in Asia will depend heavily on the realistic nature of two assumptions inherent in the 1995 simulation of the network flow model: i.e., China does not expand production beyond current levels, and both the Nauru and Christmas Island deposits are depleted.

Alternative Scenarios

Several alternative scenarios have been analyzed for purposes of demonstrating the capabilities of the models and gaining insight to the future phosphate market. Some of the scenarios are more likely than others, but all present interesting perspectives on the market. The focus of the analysis is on supply, and the variations in demand in some scenarios only serve to highlight the supply response to different underlying conditions.

The first set of scenarios involves alternative worldwide demand growth rates. The market balance model results show that resource depletion over time under the alternative assumptions about demand can be affected dramatically.

The second set of scenarios are disruption scenarios; i.e., measuring the market impacts if phosphate is suddenly not available from certain deposits or regions. This is defined in two parts; first, production from the Bou Craa deposit in Western Sahara (controlled by Morocco) is disrupted, and then all of Moroccan output is disrupted. While the second scenario appears unlikely (and rather extreme) it does provide information about Morocco's importance to the market.

Each of these disaster scenarios is addressed with both the market balance model and the network flow model. The results of the market balance model are used to illustrate the adjustments in the market over a medium- to long-term timeframe. The results of the network flow model highlight regional competition in the short run and illustrate the opportunities available for alternative suppliers.

Table 18.—Adequacy of supply from current producers at alternative demand levels

(Thousand metric tons of P_2O_5)

Year	Demand (2-pct/yr growth)	Phosphate rock shortfall		Demand (1-pct/yr growth)	Phosphate rock shortfall	
		No expansion allowed	Announced expansion occurs		No expansion allowed	Announced expansion occurs
1985	49,663	0	0	49,663	0	0
1986	50,656	0	0	50,159	0	0
1987	51,669	0	0	50,661	0	0
1988	52,702	0	0	51,167	0	0
1989	53,756	0	0	51,679	0	0
1990	54,831	0	0	52,196	0	0
1991	55,928	0	0	52,718	0	0
1992	57,047	2,510	0	53,245	0	0
1993	58,188	7,072	0	53,777	1,471	0
1994	59,351	7,903	0	54,315	1,600	0
1995	60,538	8,559	0	54,858	1,761	0
1996	61,749	11,833	4,026	55,407	5,216	0
1997	62,984	14,530	7,218	55,961	7,482	0
1998	64,244	17,001	9,334	56,521	8,897	0
1999	65,529	19,690	12,136	57,086	10,980	2,150
2000	66,839	22,604	15,268	57,657	13,371	4,721

Alternative Demand Projections

The market balance model was used in simulations to the year 2000 under two alternative assumptions for the rate of growth in world demand for phosphate products. The results (table 18) show a reduced amount of required new capacity at lower projected rates of demand growth. Comparing this information with similar information for the base case projection (using a 3-pct growth rate in demand) given in table 14 shows that only two-thirds as much new development is absolutely required at a 2-pct growth rate and only one-third as much development is needed at a 1-pct rate. When likely expansion of current producers is taken into account, almost no new property development would be required if demand grows at only 1 pct/yr.

Disruption Analyses

Two levels of supply interruption were hypothesized and included in model simulations for analysis. Both disruption scenarios assume the same level of effective demand as in the base case simulation. The lowest level of disruption assumed that no material was available from the Bou Craa deposit in Western Sahara. The most severe disruption level looked at a case where no material was available from any of the deposits in Morocco or Western Sahara. This may be a reasonable short-run scenario since there have been brief interruptions in the past. The likelihood of either of these scenarios was not addressed; they were chosen only for illustrative purposes. However, results from the models under these assumptions indicate the magnitude and types of adjustments that would be necessary. Given the possibility of civil unrest or political action in Western Sahara, a brief disruption of Moroccan supply is not inconceivable.

Results from the market balance model indicate only a minor impact if phosphate rock is no longer available from the Bou Craa deposit in Western Sahara, even if Bou Craa is disrupted for the entire forecast period. There is ample unused phosphate rock capacity in the world at present and an ample amount of potential production from new properties to replace Bou Craa phosphate rock in the future. The projected price is shown in figure 27 for both disruption scenarios and the base case discussed earlier.

The year-by-year results for the Bou Craa scenario are very similar to the base case simulation results. The average variable cost values (likely minimum price) for the Bou Craa disruption simulation are less than 5 pct higher than the base case simulation results in all years. There are many properties waiting to be developed that have average variable costs of production only slightly higher than those of current producers.

The network flow model gives a different set of results from the Bou Craa disruption scenario, however, and makes additional effects from such a disruption apparent. The loss of Bou Craa, a relatively large, low-cost source of phosphate rock, provides an opportunity for other suppliers to penetrate the markets that were supplied by that deposit. The results highlight the set of other suppliers who might be in a position to respond to an interruption of normal supply sources.

The base case design of the network is easily altered to represent a world market change. Transportation paths or arcs can be added or removed (by setting the upper bound to zero), costs changed, or specific facilities designated as closed or opened. The model is then reoptimized. By comparing the original 1984 base case optimal solution with this new optimal solution, predicted changes in material flows can be identified.

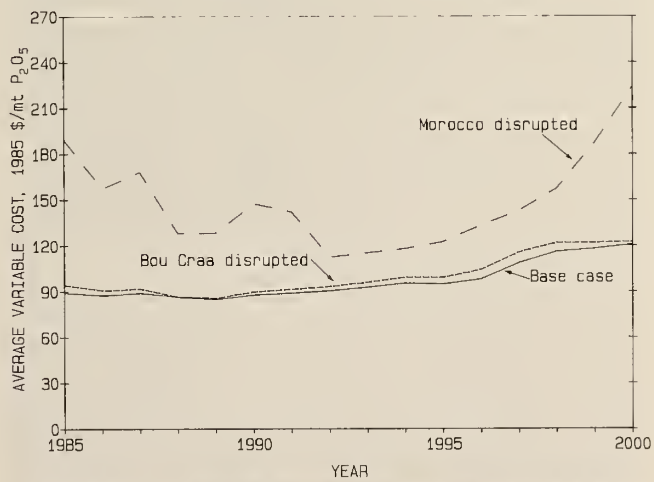

FIGURE 27. — Estimated average variable cost of marginal supplier if normal supply disrupted.

In designing the model, it has been assumed that Bou Craa phosphate rock is largely shipped to Spain as it has been in the past. Given this basic assumption, the results of a loss of Bou Craa phosphate rock could be viewed in two

ways: Spain would import phosphate rock from other sources or it would not. In the former case, approximately 700,000 mt of P_2O_5 in phosphate rock would have to be replaced. It is possible that Morocco would send production from its remaining properties to Spain. This would imply a higher cost phosphoric acid product exported from Spain, as Bou Craa is a lower cost producer of phosphate rock than most other Moroccan properties.

If alternative sources of supply, other than Morocco, were to be considered, several producers with available capacity appear to be relatively competitive in shipping phosphate rock into Spain. These include Togo, Senegal, and the United States. It is interesting to note that when many producers have the opportunity to ship to Spain, and the replacement rock is chosen on a strictly cost basis, all the business does not automatically shift to other Moroccan properties.

Analysis of Spanish import-export data for phosphate rock compared with phosphoric acid plant capacity indicates that Spain may be a reexporter of phosphate rock. When low-cost sources of phosphate rock are no longer available, this may not remain the case. However, Spanish phosphoric acid remains cost competitive even with somewhat higher cost phosphate rock, so it is probable that at least enough phosphate rock to supply the phosphoric acid plants would be imported.

Were Spain to stop exporting phosphoric acid, its market share would be available to alternative suppliers. In particular, cost-competitive alternative suppliers of phosphoric acid to Western and Eastern Europe would be in a position to gain market share. Their ability to do so in the short run would be limited by available capacity. In both of these cases, the phosphate rock markets appear able to adapt to the loss of Bou Craa without major disruption.

The second disruption scenario involves an interruption of supplies from all Moroccan deposits. The market balance model results show that the already-developed deposits in the rest of world can replace the phosphate rock no longer available from Morocco, but at a very high cost (fig. 27). The average variable cost at the highest cost, or marginal, producer is immediately almost double the base case value, as some very high cost properties (assumed temporarily shut down in the base case solution of the market balance model) are brought back into production. The estimated cost level decreases slowly as new properties are developed. The slight rises in several of the early years of the simulation indicate that resources at some currently producing properties are being depleted faster than new capacity is being developed for those years. The average variable cost value tends to continue to drop as long as there are new properties being developed with average variable costs lower than some of the already producing properties.

The currently nonproducing properties that require the longest lead times would all be developed and producing by the early 1990's, and from that point onward, the cost level would rise at a pace determined by demand growth and depletion of resources. By the year 2000, the required supply of phosphate rock would have to come from very high cost properties, deposits that would not be developed under normal circumstances. Were conditions even remotely similar to such a disruption to occur, it is more probable that many of the resources now in the inferred category would be proved up by exploration to the demonstrated level, and the costs could be far below that shown in figure 27.

Results from the network flow model simulation show additional pieces of information. The full Moroccan disruption has enormous implications for the pattern of production and trade.

Morocco is an important exporter of phosphate rock and phosphoric acid products to many markets, particularly Western and Eastern Europe. There would undoubtedly be shifts in market shares held by alternative suppliers of phosphate rock into these markets. The delivered cost from the marginal supplier would likely be higher than it is now. However, given that increased exports from producers with excess capacity are directed to Western Europe in the network design, adequate mine and mill capacity is currently available worldwide to replace all Moroccan phosphate rock production. This adequacy of capacity is demonstrated without the need to deplete current phosphate rock inventories.

The United States currently exports over 750,000 mt of P_2O_5 in rock product to Western Europe (*12*). If Morocco were to cease exporting phosphate rock, U.S. producers would appear to be in a competitive position to increase exports to that market. In fact, even with Morocco producing, the results of the network flow model indicate that U.S. exports into Western Europe are competitive with some current suppliers on a strictly cost basis. While there are lower cost properties than the marginal U.S. property supplying Western Europe, their capacity is not adequate to fulfill the entire market demand. Further, the United States is not the marginal supplier of phosphate rock to Western Europe.

Another interesting aspect of a disruption of Moroccan production is world phosphoric acid capacity. Morocco had phosphoric acid plant capacity for approximately 1.5 million mt of P_2O_5 in 1984 (*22*), divided among four plants. In the base case solution, all four were producing at capacity. Were they to temporarily shut down, alternative phosphoric acid capacity would be needed. The base case solution shows the capacity of idle phosphoric acid plants to be approximately 2.2 million mt of P_2O_5.

Apparently, there currently exists phosphoric acid capacity adequate to replace all Moroccan phosphoric acid exports. Approximately 10 pct of the idle capacity is located in Western Europe, with the balance distributed worldwide. Many of the plants shown idle in the network are in locations physically remote from either their phosphate rock supply and/or Europe. In the base case solution, the United States and Canada have idle phosphoric acid plant capacity in an amount equal to over 30 pct of the Moroccan capacity. Although the plants predicted to be idle are in several instances far from eastern Canada or U.S. ports, their output could be exported. With shifting trading patterns, traditional suppliers of phosphoric acid products to Europe who are predicted to have idle phosphoric acid capacity could gain market share. These could include the United States, Canada, the Republic of South Africa, Israel, Senegal, and possibly Japan and the Republic of Korea.

CONCLUSIONS

The agricultural industry worldwide is dependent upon the supply of fertilizers derived from phosphate rock. The Bureau of Mines is looking at the level, conditions, and determinants of phosphate supply both in the current year and in the future. A necessary first step toward this objective is to reexamine world resources, production capacity, and costs. This updated information is placed into a market context in the form of computerized mineral market models. By so doing, the "snapshot" description of phosphate provided by an availability study is expanded to allow for a variety of assumptions concerning the economic and political realities facing the industry.

The Bureau evaluated 206 mines and deposits in 30 MEC's and investigated the resource potential of mines and deposits in China and the U.S.S.R. The selected mines and deposits include all known resources of phosphate rock at the demonstrated resource level that met the criteria of the study and can be mined and milled with current technology.

Approximately 35.1 billion mt of phosphate rock is potentially recoverable from the demonstrated resources of the mines and deposits evaluated in MEC's. An additional 1.5 billion mt of phosphate rock is potentially recoverable from mines and deposits in China and the U.S.S.R. Morocco has the largest resource, with 21.6 billion mt of recoverable phosphate rock, followed by the United States with 6.1 billion mt.

Total MEC production from the demonstrated resource base in 1985 was more than 106 million mt. This indicates approximately 76 pct capacity utilization. The United States produced nearly 51 million mt (47 pct of the total), while Morocco produced about 21 million mt (20 pct of the total). CPEC production was an additional 45 million mt.

Potential annual capacity from currently producing mines in the United States could decline from about 67 million mt in 1987 to under 41 million mt by late in the next decade, as the demonstrated resources of some producing mines become exhausted. (The rate of capacity decline will be determined by the actual rate of production.) However, the annual capacity of currently producing mines in Morocco is estimated to decrease only slightly by 1997 to 28 million mt (from 30 million mt in 1987). Assuming fixed capacities for existing mines and U.S. production remaining at least at 1985 levels, more than half of U.S. production in 1997 would come from mines yet to be developed.

Undeveloped deposits in the United States contain a demonstrated resource of 400 million mt of recoverable phosphate rock, which could be developed and produced for under $50/mt (including a 15-pct DCFROR). If developed concurrently, the deposits could have a potential annual capacity of 16 million mt of phosphate rock in the year N+10 of the analysis, at total production costs under $50/mt. In comparison, much of the competing phosphate rock from existing mines in Morocco (most of which have sufficient resources to last well into the next century) can be produced for under $40/mt. This fact, combined with Morocco's cost advantage in shipping phosphate rock to major consuming markets, indicates that the cost advantage in the world phosphate rock export industry may shift from Florida to Morocco in the future.

Morocco and several other phosphate-producing countries are constructing new phosphoric acid plants to process phosphate rock, which means that as the average cost of domestic phosphate rock increases, the United States will also face serious competition in the export markets for phosphoric acid and related fertilizer products. The United States is the largest consumer of phosphate fertilizers and should remain as the main supplier of phosphate products domestically and to Canada. However, the U.S. phosphate industry will face competition from other producing countries in all other major markets.

The market models were developed so that Bureau analysts could examine the cost and resource data within a market context and thereby be better able to assess the relative competitive position of U.S. suppliers under different sets of assumptions. The production potential discussed in the "Availability" section of this study is coupled with the supply model methods for estimating actual production levels. Both forms of market models (market balance and network flow) assume that production will come from the potential supply source with the lowest cost. This supply perspective is used to determine rates of resource depletion at all MEC deposits that are consistent with estimates of demand and other market conditions.

Results from a base case projection using the market balance model show that with a 3-pct growth rate in demand, already-developed production capacity is sufficient to satisfy worldwide demand until 1990. If already-announced expansion plans are presumed to take place, then current producers will have sufficient capacity to satisfy demand a year or two longer than that. If the growth rate for consumption is as low as 1 pct/yr, current capacity could be sufficient until the mid to late 1990's, depending on whether there is expansion at already-developed properties.

Allowing for a small surplus of production capacity over required supply (i.e., estimated demand growth of 3 pct/yr), results from the market balance model suggest that nearly 36 million mt (P_2O_5) of new capacity will be developed by the year 2000, most of that from new properties. The capital costs for this development will be significant, over $8 billion. Total costs at new properties likely to be developed by the year 2000 are in the $60/mt to $70/mt (of phosphate rock) range at a 15-pct DCFROR and in the $40/mt to $45/mt range at a 0-pct DCFROR. Average variable costs at those properties (a necessary minimum price) will be in the $35/mt to $40/mt (of phosphate rock) range, a 25- to 50-pct increase over current cost levels and market prices.

Results from the network flow model indicate the current competitive positions of alternative suppliers to each of the major consuming regions. Markets for both phosphate rock and phosphoric acid have been examined. The United States is shown to be reasonably competitive in many markets for both phosphate rock and phosphoric acid. However, U.S. producers do not have the lowest delivered cost for phosphate products in any markets except Canada and the United States. Additionally, major changes to transportation rates, which are a very large percentage of delivered cost, could affect the costs of delivered U.S. phosphate relative to phosphates from suppliers located closer to some demand regions. The higher costs associated with the yet-to-be-developed deposits in the southern extension in Florida will also mean increased competition in both domestic and export markets from other supply sources in the future.

From the perspective of the phosphate consumer, the United States is in an enviable position. Phosphate products

can be delivered at lower cost to U.S. consumers than they can to any of the other major phosphate-fertilizer-using areas in the world. This is likely to remain true for at least the rest of the century. Western Europe is the major consuming region with the next lowest delivered costs for phosphate products, incurring 10 to 15 pct additional production and transportation charges for material from most of its traditional sources. The Asian market, most of which is far from the principal supply sources, shows median delivered costs 20 to 30 pct higher than those borne by U.S. consumers.

Both models were also used to examine various disruption scenarios. The loss of small amounts of production capacity have very little impact on the market. The large amount of excess capacity currently available ensures that material from other deposits would be available at only slight increases in cost.

The loss of larger amounts of production capacity was also examined. Results from the market balance model show that current capacity is sufficient to replace phosphate material from a disruption of a supply source as large as all of Morocco. Even over a long-time horizon, it is shown that current capacity plus demonstrated resources waiting to be developed are sufficient to replace material lost in such a disruption. The increase in costs, however, would be substantial, especially in a 2- to 4-yr interim period while new property development took place.

Results from the network flow model indicate that there is also sufficient phosphoric acid capacity to make up for such a disruption in supplies. Major shifts from traditional trading patterns would be required, however, and there would be substantial increase in delivered cost of phosphate products in virtually all markets.

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APPENDIX A.—WORLD MINE AND DEPOSIT STATUS AND INFORMATION[1]

This study assumes that 82 MEC mines were in production as of the beginning of 1985 (34 in the United States and 48 in foreign countries, not including CPEC's). The study also includes 124 nonproducing deposits (90 in the United States and 34 foreign), comprising deposits that are developing or have definite developmental plans as well as many deposits that are just explored prospects. Table A-1 lists all the mines and deposits included in the study and provides information on the actual or proposed mining operation.

UNITED STATES

The majority of the U.S. producing properties are located in Florida, with 22 mines, owned and operated by 13 companies, all producing phosphate rock for phosphoric acid plant feed or export. The International Minerals and Chemicals (IMC) Corp. operates the Kingsford, Noralyn, and Clear Springs Mines, all in Polk County. W.R. Grace & Co. operates the Hookers Prairie Mine in Polk County and is coowner of the newly commissioned joint venture Four Corners Mine (with IMC) in Polk and Manatee Counties. W.R. Grace's Bonny Lake Mine, now depleted, was not included in the study. Agrico Chemical Co. operates the Fort Green, Payne Creek, and Saddle Creek Mines, all in Polk County. Mobil Chemical Co. operates a mine near Fort Meade as well as its Nichols Mine, both in Polk County. Estech General Chemical Co. operates two mines in Polk County, the Silver City Mine and the Watson Mine. The Haynesworth Mine in Polk County and the Lonesome Mine in Hillsborough County are operated by Brewster Phosphates. The remaining two mines in Polk County are USS Agri-Chemical's Rockland Mine and Gardinier Inc.'s mine near Fort Meade. Two mines are operated by Occidental Chemical Co. in Hamilton County: the Suwannee River and Swift Creek Mines. Beker Industries operates the Wingate Creek Mine in Manatee County. Hardee county contains the C. F. Industries complex near the Polk County line, and Hillsborough County contains the newly opened Hopewell Mine owned by Noranda, and the Big Four Mine owned by Mobil. The Big Four Mine has been idle since 1982.

A slowdown in phosphate demand growth and lower than normal prices since 1981 have led to shutdowns, shorter workweeks, and otherwise reduced output levels for the Florida industry. Most of the mines listed above have at one time or another experienced these conditions over this period and there is presently a realignment of ownership occurring within the industry. The only deposits being considered for development in the near future in Florida are Mobil's South Fort Meade Mine and a mine in southeast Hillsborough County being considered by IMC.

The study also included 40 explored prospects in Florida whose resources could become available sometime in the future. A majority of these prospects are located in Florida's southern extension, an extension of the currently mined central district. Mines in this area will have higher stripping ratios, and ores will have generally lower grades and a higher magnesium content than ores in the area currently being mined. Included in the 40 deposits are such prospects as AMAX's Pine Level, Kerr McGee Chemical Corp.'s Brooker Dukes (in Alachua County), Freeport's Acrefoot Johnson, and many others.

In North Carolina, Texasgulf Chemical Corp. operates the Lee Creek Mine, and the North Carolina Phosphate Corp. (recently purchased by Texasgulf) had initiated development on the Canvas Creek Mine (which could have been operational by the end of this decade if developmental efforts had continued). Both operations produce or would produce phosphate rock for phosphoric acid plant feed or export.

Operations in Tennessee are owned by Hooker Chemical Co., Monsanto Industrial Chemical Co., and Stauffer Chemical Co. Some tracts in Tennessee are owned by the Tennessee Valley Authority (TVA). Production in Tennessee in the past has gone to produce elemental phosphorus. Monsanto was expected to cease operations in Tennessee by 1987.

In the Western United States, Chevron Resources Co. operates the Vernal, UT, mine (whose capacity was to be expanded in 1986). Cominco American Inc., operates the only underground phosphate rock mine in the United States (the Warm Springs Creek Mine near Garrison, MT). In Idaho, five companies operate six mines. J. R. Simplot Co. operates the Gay and Conda-Smokey Canyon Mines. The Gay Mine produces acid-grade phosphate rock for Simplot and electric furnace feed (elemental phosphorus production) for FMC Corp. Smokey Canyon Mine phosphate rock is calcined in Conda and shipped to Pocatello for phosphoric acid production. Stauffer Chemical Co. ships phosphate rock from its Wooley Valley Mine to electric furnaces at Silver Bow, MT. The Conda Partnership, jointly owned by Beker Industries Corp. and by Western Cooperative Fertilizers Ltd., produces phosphate rock from the Maybe Canyon (also known as Dry Valley) and Champ Mines for phosphoric acid feed. These two operations were closed throughout most of 1986 owing to the financial difficulties of Beker Industries. Monsanto sends phosphate rock from its Henry Mine (and its North Henry Extension) to electric furnaces at Soda Springs, ID. Alumet Corp. produces phosphate rock at its Lane Creek Mine. The study also includes the future potential developments of Enoch Valley (Monsanto), Diamond Creek (Alumet), Rasmussen Ridge (Stauffer), and Dry Valley (FMC), all in Idaho, as well as 42 additional explored prospects in Utah and Wyoming.

Expected future production from the operations in Tennessee and some of the operations in Idaho is included only indirectly in the market models, since none of the material at those mines is used for fertilizer production (the market that the model simulations focus on). These properties cannot be presumed to respond to the demand and price conditions in the fertilizer market, and a prespecified production level is entered into the market model data base as production from other sources.

[1] The worldwide ownership and status information reported in this appendix is correct for the period of the analysis (1985).

Table A-1.—World phosphate properties included in study

Country and deposit name	Owner	Status[1]	Mine method[2]	Mill method[3]	Deposit type[4]	Initial production year[5]	Feed grade, wt pct	Mill capacity[6] 10^3 t	Production grade, wt pct	Production capacity[6] 10^3 mt
Algeria: Djebel Onk	Algerian Government (SONAREM)	P	OP	S	SED	1965	24.6	3,500	31.8	2,000
Angola: Lacunga River	Angolan Government (Fosfang)	E	SL	W	SED	—	19.4	500	34.0	200
Australia:										
Christmas Island	Phosphate Mining Co. of Christmas Island.	P	SL	S	SED	1965	33.4	2,200	36.0	1,500
D-Tree	IMC Development Corp	E	SL	F	SED	—	18.6	8,600	34.0	4,000
Duchess	Western Mining Corp	T	SL	S	SED	1975	18.4	200	31.0	200
Lady Annie, Lady Jane	..do	E	SL	F	SED	—	17.0	9,400	34.0	4,000
Laverton	Australian Government and Union Oil	E	OP	F	SED	—	20.0	2,100	38.0	1,000
Northern deposits	Western Mining Corp	E	SL	F	SED	—	15.1	7,900	34.0	3,000
Brazil:										
Anitapolis	Industrias Luchsinger Madorin (ILM)	D	SL	F	IGN	1986	6.5	3,800	35.1	600
Araxa-Arafertil	Arafertil	P	OP	F	IGN	1977	14.0	3,100	36.0	500
Araxa-Camig	..do	P	OP	F	IGN	1976	14.0	900	26.3	200
Catalao-Fosfago	Fosfago de Goias, S.A	P	OP	F	IGN	1980	10.0	2,800	38.0	500
Catalao-Goiasfertil	Goias Fertilizantes	P	OP	F	IGN	1976	8.9	4,400	38.0	600
Ipanema I and II	Serrana, S.A	E	OP	F	IGN	—	7.0	4,100	38.0	500
Itataia	Nuclebras	D	SL	F	HYD	—	11.0	2,000	33.0	500
Jacupiranga	Serrana, S.A	P	OP	F	IGN	1965	5.0	4,300	35.0	500
Olinda-Paulista-Igarassu	FOSPERSA	E	SL	F	SED	—	20.0	700	28.0	300
Patos de Minas	Fertilizantes Fosfatos, S.A	P	SL	F	SED	1977	13.0	3,200	30.0	1,000
Tapira	Fosfertil, S.A	P	OP	F	IGN	1979	7.3	10,000	36.0	1,200
Canada:										
Cargill	Sherritt Gorden Mines	E	OP	F	IGN	—	20.0	1,900	39.0	700
Martison Lake	Campbell, New Venture	E	OP	F	IGN	—	17.5	1,300	39.0	400
Colombia: Pesca-Conejera-Sardinata	Colombia Government (Ecominas)	PP	R&P	F	SED	—	18.0	400	29.0	100
Egypt:										
Abu Tartur	Arab Republic of Egypt	E	LW	F	SED	—	25.3	3,600	31.0	1,500
Hamrawein	Misr Phosphates	P	R&P	W	SED	1978	10.1	1,200	30.0	600
Quseir	Red Sea Phosphate Co	P	R&P	W	SED	1980	21.0	200	26.0	100
Sabaiya East	Abu Zaabel Fertilizer Chemical Co	P	R&P	S	SED	1977	26.0	100	26.0	100
Sabaiya West	..do	P	SL	F	SED	1977	22.0	900	28.0	500
Safaga	Red Sea Phosphate Co	P	R&P	S	SED	1979	26.0	200	29.0	200
Finland:										
Siilinjarvi	Kemira Oy (Government of Finland)	P	OP	F	IGN	1980	4.0	6,000	35.9	500
Sokli	Rautaruukki Oy	E	OP	F	IGN	—	18.0	1,200	38.0	500
India: Jhamarkotra	Rajasthan State Mines & Minerals, Ltd.	P	OP	F	SED	1970	20.9	1,700	31.7	1,500
Iraq: Akashat	State Organization for Minerals	P	SL	C	SED	1981	21.0	3,400	31.8	1,700
Israel:										
Arad	Negev Phosphates Ltd	P	SL	W	SED	1970	27.0	900	32.6	500
Beersheba	..do	E	SL	W	SED	—	26.8	3,200	32.0	2,000
Nahal Zin	..do	P	SL	W	SED	1978	26.8	3,200	32.0	2,000
Oron	..do	P	OP	W	SED	1965	23.5	1,000	34.3	500
Jordan:										
El Hasa, El Abiad	Jordan Phosphate Mining Co	P	SL	W	SED	1970	29.8	9,400	33.7	5,700
Esh Shidiyah	..do	D	SL	F	SED	1987	25.4	3,800	33.4	2,000
Ruseifa	..do	P	SL	W	SED	1965	25.0	1,750	32.0	1,000
Mexico:										
San Juan de la Costa	Government of Mexico (ROFOMEX)	P	OP	F	SED	1980	18.0	2,000	31.0	800
Santo Domingo	..do	D	DR	F	SED	1990	4.5	11,200	30.0	1,200
Morocco:										
Ben Guerir	Government of Morocco (OCP)	P	SL	W	SED	1981	24.0	5,200	30.2	3,000
Daoui-Recette 4	..do	P	SL	W	SED	1971	26.0	17,000	32.1	10,000
Khouribga underground	..do	P	R&P	S	SED	1965	29.0	2,400	32.3	1,600
Meraa el Arech	..do	P	SL	S	SED	1965	25.0	9,600	32.1	5,00

See notes at end of table.

Table A-1.—World phosphate properties included in study—Continued

Country and deposit name	Owner	Status[1]	Mine method[2]	Mill method[3]	Deposit type[4]	Initial production year[5]	Feed grade, wt pct	Mill capacity[6] 10^3 t	Production grade, wt pct	Production capacity[6] 10^3 mt
Morocco—Continued:										
Meskala District	..do	E	SL	W	SED	—	29.7	2,800	31.0	2,000
Recette-10	..do	E	SL	W	SED	—	25.0	4,200	32.1	2,500
Sidi Chennane	..do	E	SL	W	SED	—	25.0	3,900	32.0	2,000
Sidi Hajjaj	..do	E	SL	W	SED	1990	24.0	4,300	31.0	2,000
Youssoufia Black Rock	..do	P	LW	S	SED	1974	27.5	6,300	34.0	3,600
Youssoufia White Rock	..do	P	R&P	S	SED	1980	29.0	6,400	31.0	4,000
Nauru: Nauru	Nauru Phosphate Corp	P	SL	S	SED	1965	38.4	2,900	39.4	2,000
Pakistan:										
Kakul-Hazara	Sarhad Development Authority	D	C&F	S	SED	1986	28.5	60	33.0	40
Lagarban-Hazara	..do	D	C&F	S	SED	1990	27.0	400	34.0	200
Peru: Bayovar	Probayovar S.A.	E	SL	W	SED	—	7.8	7,400	30.5	1,500
Saudi Arabia: West Thaniyat	Government of Saudi Arbia, Granges International.	E	LW	S	SED	—	22.0	5,000	35.0	2,500
Senegal:										
Pallo (Thies)	Senegal Government, Rhone-Poulenc	P	SL	S	SED	1965	28.0	720	30.0	600
Taiba-Tobene	Senegal Government, BRGM, INC	P	SL	F	SED	1965	26.9	6,400	33.4	1,500
South Africa, Republic of: Palabora (Foskor).	Foskor (Phosphate Development)	P	OP	F	IGN	1965	6.0	23,900	36.5	3,200
Sri Lanka: Eppawella	Sri Lankan Government (SMMDL), Agrico.	E	OP	S	SED	—	32.0	900	32.0	900
Syria:										
Kneifess	Gecopham (General Co. for Phosphates)	P	OP	S	SED	1971	28.0	1,000	32.0	600
Sharkya A.	..do	P	OP	S	SED	1974	24.0	1,400	30.0	800
Sharkya B.	..do	P	OP	S	SED	1974	26.0	1,300	30.0	800
Togo:										
Dagbati	Togo Government (COTOMIB)	E	OP	W	SED	—	30.0	2,700	36.0	1,500
Hahotoe-Kpogame	..do	P	SL	W	SED	1965	28.0	6,000	36.0	3,200
Tunisia:										
Djellabia	CIE des Phosphates de Gafsa (Government).	D	SL	S	SED	1992	25.5	2,300	30.2	1,500
Kalaa Khasba	..do	P	R&P	W	SED	1980	27.0	300	30.0	200
Kef Eddour	..do	D	SL	S	SED	1987	25.5	2,150	30.2	1,400
Kef Eschfair	..do	P	SL	W	SED	1972	25.5	1,950	30.2	1,300
M'Dilla	..do	P	R&P	W	SED	1965	25.5	750	30.2	500
Metlaoui	..do	P	R&P	W	SED	1975	25.5	800	30.2	500
Moulares	..do	P	R&P	W	SED	1965	25.0	1,300	30.2	800
M'Rata	..do	P	R&P	W	SED	1965	25.5	1,300	30.2	900
Oum El Khecheb	..do	D	SL	S	SED	1990	25.5	450	30.2	300
Redeyef	..do	P	R&P	S	SED	1965	25.0	1,000	28.0	700
Sehib	..do	P	LW	W	SED	1978	25.5	2,100	30.2	1,400
Sra Ouertane	..do	D	SL	F	SED	1992	15.0	3,800	29.0	1,200
Turkey: Mardin-Mazidag	Etibank	P	CF	F	SED	1985	18.0	300	30.0	100
Uganda: Sukulu Hills	Sukulu Mines Ltd	D	OP	F	IGN	1989	11.7	400	42.0	100
United States:										
Florida:										
Acrefoot Johnson	Freeport Phosphate Mining Co	E	SL	F	SED	—	5.1	16,800	30,0	2,700
Big Four	Mobil Chemical Co	T	SL	F	SED	1977	W	W	W	W
Boyette and Fishawk	Agrico Chemcial Co	E	SL	F	SED	—	7.4	3,800	33.9	700
Brooker-Dues	Kerr-McGee Chemical Corp	E	SL	F	SED	—	6.5	13,870	31.6	2,700
C. F. Hardee Phosphate Complex	C. F. Industries Inc	P	SL	F	SED	1978	W	W	W	W
Christina	Mobil Chemical Co	E	SL	F	SED	—	8.0	2,100	33.4	500
Clear Springs	IMC Corp	P	SL	F	SED	1948	W	W	W	W
Cooks Hammock #1	Monsanto Co	E	SL	F	SED	—	4.3	4,200	33.0	500
Cooks Hammock #2	Unidentified major paper company	E	SL	F	SED	—	4.3	3,600	32.0	500
David C. Turner Heirs	Heirs of D. C. Turner	E	SL	F	SED	—	4.7	3,500	30.2	500
Deep Creek	Occidental Chemical Co	E	SL	F	SED	—	4.8	15,400	31.4	1,800

See notes at end of table.

Table A-1.—World phosphate properties included in study—Continued

Country and deposit name	Owner	Status[1]	Mine method[2]	Mill method[3]	Deposit type[4]	Initial production year[5]	Feed grade, wt pct	Mill capacity[6] 10^3 t	Production grade, wt pct	Production capacity[6] 10^3 mt
United States—Continued:										
Florida—Continued:										
Deseret Ranch	Mormon Church	E	SL	F	SED	—	5.5	42,000	28.6	5,500
DeSoto-Manatee Reserve	Mobil Chemical Co	E	SL	F	SED	—	6.1	18,100	30.7	3,400
Duette	Estech	E	SL	F	SED	—	5.2	15,950	31.0	2,700
Durrance, Waters Tract	U.S.S. Agri-Chemicals	E	SL	F	SED	—	5.5	5,100	30.7	900
Farmland Hardee	Farmland Industries Inc	E	SL	F	SED	—	7.6	6,800	31.2	1,800
First Mississippi Chemical Tract	First Mississippi Chemical Corp	E	SL	F	SED	—	6.5	2,800	33.3	500
Fort Green	Agrico Chemical Co	P	SL	F	SED	1975	W	W	W	W
Fort Meade #1	Mobil Chemical Co	P	SL	F	SED	1945	W	W	W	W
Fort Meade #2	Gardinier Inc	P	SL	F	SED	1967	W	W	W	W
Four Corners	W. R. Grace & Co. and IMC Corp	P	SL	F	SED	1985	W	W	W	W
Fridovich	Agri-Lewis Corp	E	SL	F	SED	—	7.1	2,500	32.6	500
Hardee	First Mississippi Chemical Corp	E	SL	F	SED	—	5.2	17,800	30.7	2,700
Hardee West	Various ownerships	E	SL	F	SED	—	4.3	7,800	30.3	900
Haynesworth	Brewster Phosphates	P	SL	F	SED	1965	W	W	W	W
Hillsborough Co.-Farmland Brewster	Pruitt, Thompson, Jameson, Simms	E	SL	F	SED	—	5.7	3,200	33.3	500
Hookers Prairie	W. R. Grace & Co	P	SL	F	SED	1976	W	W	W	W
Hopewell	Noranda	P	SL	F	SED	1985	W	W	W	W
Keys	IMC Corp	E	SL	F	SED	—	4.0	25,000	29.6	2,300
Kingsford	..do	P	SL	F	SED	1965	W	W	W	W
La Crosse	Kerr-McGee Chemical Corp	E	SL	F	SED	—	6.2	2,800	31.6	500
Little Payne Creek	U.S.S. Agri-Chemical Gardiner, others	E	SL	F	SED	—	7.3	9,300	30.9	2,700
Lonesome	Brewster Phosphates	P	SL	F	SED	1976	W	W	W	W
Manatee North	W. R. Grace & Co	E	SL	F	SED	—	5.6	17,700	29.9	2,700
Manatee South	..do	E	SL	F	SED	—	4.2	31,400	30.2	3,600
Manson-Jenkins	U.S.S. Agri-Chemicals	E	SL	F	SED	—	5.1	5,800	30.5	900
Mobil Area	Various ownerships	E	SL	F	SED	—	4.8	7,700	30.9	1,100
N.E. Manatee Swift, Grace	W. R. Grace & Co. and others	E	SL	F	SED	—	4.7	3,500	30.4	500
Nichols	Mobil Chemical Co	P	SL	F	SED	1970	W	W	W	W
North Columbia County #2	South Resin Corp	E	SL	F	SED	—	3.9	17,400	28.4	1,800
Noralyn, Phosphoria	IMC Corp	P	SL	F	SED	1948	W	W	W	W
North Lake City	Kerr-McGee Chemical Corp	E	SL	F	SED	—	6.1	2,600	31.1	500
Northeast Manatee, Texaco	Various ownerships	E	SL	F	SED	—	3.8	8,800	30.7	900
Osceola National Forest	U.S. Forest Service	E	SL	F	SED	—	4.8	13,000	31.2	1,800
Payne Creek	Agrico Chemical Co	P	SL	F	SED	1966	W	W	W	W
Pierce-Pebbledale	..do	E	SL	F	SED	—	5.1	3,100	31.4	500
Pine Level	Mobil Chemical Co	E	SL	F	SED	—	6.1	6,750	30.7	1,400
Rockland	U.S.S. Agri-Chemicals and Freeport Phosphate Co.	P	SL	F	SED	1968	W	W	W	W
Rutland-Colvin-Vale	IMC Corp	E	SL	F	SED	—	3.1	13,100	29.8	1,100
Saddle Creek	Agrico Chemical Co	P	SL	F	SED	1950	W	W	W	W
Sarasota County No. 1	George Kelce	E	SL	F	SED	—	2.9	16,100	27.8	1,400
SE Hillsborough Reserves	IMC Corp	E	SL	F	SED	—	W	W	W	W
Silver City	Estech	P	SL	F	SED	1964	W	W	W	W
South Fort Meade	Mobil Chemical Co. and others	D	SL	F	SED	1990	W	W	W	W
South Hardee	Gardinier Inc	E	SL	F	SED	—	4.4	15,100	29.9	2,300
Suwannee River	Occidental Chemical Co	P	SL	F	SED	1965	W	W	W	W
Swift Creek	..do	P	SL	F	SED	1975	W	W	W	W
Swift-Durrance Area	Various ownerships	E	SL	F	SED	—	5.2	3,500	31.0	500
Texaco Manatee	Texaco Inc	E	SL	F	SED	—	6.1	8,700	30.7	1,400
Waters Tract	U.S.S. Agri-Chemicals	E	SL	F	SED	—	4.2	6,500	29.6	900
Watson	Estech	P	SL	F	SED	1936	W	W	W	W
Wingate Creek	Beker Industries	P	SL	F	SED	1982	W	W	W	W
Zolfo Springs area small ownerships	Mining Development Corp	E	SL	F	SED	—	7.0	6,000	30.4	1,100
Zolfo-Stauffer	Stauffer Chemical Co	E	SL	F	SED	—	5.9	6,000	32.0	900
Idaho:										
Diamond Creek	Alumet Corp	E	OP	C	SED	—	W	W	W	W
Dry Valley	J. R. Simplot Co. and FMC Corp	D	OP	W	SED	1987	W	W	W	W
Enoch Valley	Monsanto Co	D	OP	W	SED	1991	W	W	W	W
Gay Mine	J. R. Simplot Co. and FMC Corp	P	OP	W	SED	1946	W	W	W	W

See notes at end of table.

Table A-1.—World phosphate properties included in study—Continued

Country and deposit name	Owner	Status[1]	Mine method[2]	Mill method[3]	Deposit type[4]	Initial production year[5]	Feed grade, wt pct	Mill capacity[6] 10^3 t	Production grade, wt pct	Production capacity[6] 10^3 mt
United States—Continued										
Idaho—Continued:										
Henry, North Henry	Monsanto Co	P	OP	W	SED	1952	W	W	W	W
Lanes Creek	Alumet Corp	P	OP	C	SED	1978	W	W	W	W
Maybe Canyon, Champ, others	Conda Partnership	P	OP	C	SED	1966	W	W	W	W
Rasmussen Ridge	..do	D	OP	W	SED	1994	W	W	W	W
Smokey Canyon	J. R. Simplot Co	P	OP	W	SED	1920	W	W	W	W
Wooley Valley	Stauffer Chemical Co	P	OP	W	SED	1955	W	W	W	W
Montana: Warm Springs Creek	Cominco American Inc	P	R&P	S	SED	1929	W	W	W	W
North Carolina:										
Canvas Creek	North Carolina Phosphate Corp	D	SL	F	SED	1989	W	W	W	W
Lee Creek	Texasgulf Chemcial Corp	P	SL	F	SED	1966	W	W	W	W
Tennessee:										
Hooker Chemical Properties	Hooker Chemical Co	P	SL	W	SED	1953	W	W	W	W
Monsanto Properties	Monsanto Co	P	SL	W	SED	1938	W	W	W	W
Stauffer Chemical Co. Property	Stauffer Chemical Co. and others	P	SL	W	SED	1896	W	W	W	W
Tennessee Valley Authority	Tennessee Valley Authority	PP	SL	W	SED	—	W	W	W	W
Utah:										
Central Wasatch Range #1	Public land, unleased	E	OP	F	SED	—	24.1	300	28.7	200
Central Wasatch Range #2	..do	E	OH	F	SED	—	20.1	1,250	28.8	700
Crawford Mountains #1	Stauffer Chemical Co	E	OP	F	SED	—	23.7	1,000	28.4	800
Crawwford Mountains #2	..do	E	OP	F	SED	—	23.7	1,000	28.4	800
Crawford Mountains #3	..do	E	R&P	F	SED	—	19.5	250	26.0	100
Crawford Mountains #4	..do	E	R&P	F	SED	—	26.7	1,250	33.0	800
Crawford Mountains #5	..do	E	R&P	F	SED	—	20.5	250	28.7	100
Flaming Gorge #1	Public land, unleased	E	OP	F	SED	—	23.1	1,000	29.0	700
Flaming Gorge #2	..do	E	R&P	F	SED	—	20.4	1,250	26.0	900
Flaming Gorge #3	..do	E	R&P	F	SED	—	19.4	250	26.0	200
Northern Wasatch Range	..do	E	OP	F	SED	—	26.3	1,000	32.4	700
Vernal Field #1	U.S. Steel	E	OP	F	SED	—	20.6	1,000	26.0	700
Vernal Field #2	..do	E	OP	F	SED	—	20.8	1,000	26.0	700
Vernal Field #3	..do	E	R&P	C	SED	—	19.1	1,250	26.0	800
Vernal Filed #4	..do	E	R&P	C	SED	—	16.9	2,500	26.0	1,300
Vernal Field #5	..do	E	R&P	C	SED	—	17.1	1,250	26.0	700
Vernal Mine	Chevron Resources	P	OP	F	SED	1961	W	W	W	W
Wyoming:										
Gros Ventre Range #1	Public land, unleased	E	OP	F	SED	—	25.5	1,000	33.0	700
Gros Ventre Range #2	..do	E	OH	C	SED	—	20.9	5,000	26.4	3,500
Hoback Range #1	..do	E	OP	F	SED	—	21.5	1,000	28.0	700
Hoback Range #2	..do	E	OP	F	SED	—	20.9	1,000	26.0	700
Hoback Range #3	..do	E	OH	F	SED	—	19.6	1,250	26.0	800
S.E. Wind River Range #1	..do	E	OP	F	SED	—	20.2	1,000	26.0	700
S.E. Wind River Range #2	..do	E	R&P	C	SED	—	18.1	2,500	26.0	1,400
Salt River Range #1	..do	E	OP	F	SED	—	24.9	1,000	30.2	800
Salt River Range #2	..do	E	OH	F	SED	—	18.3	2,500	26.0	1,300
Salt River Range #3	..do	E	OH	F	SED	—	24.6	1,250	33.0	600
Snake River #1	..do	E	OP	F	SED	—	25.9	1,000	30.4	800
Snake River #2	..do	E	R&P	F	SED	—	22.3	5,000	29.2	2,900
Snake River #3	..do	E	OP	S	SED	—	24.5	1,000	30.7	700
Snake River #4	..do	E	R&P	F	SED	—	20.4	1,250	30.3	500
Snake River #5	..do	E	R&P	F	SED	—	24.3	250	33.0	100
South Ridges #1	..do	E	OP	F	SED	—	23.2	1,000	28.8	700
South Ridges #2	..do	E	OH	F	SED	—	19.6	1,250	29.0	500
South Ridges #3	..do	E	OH	F	SED	—	22.9	5,000	27.2	3,000
Sublette Range #1	..do	E	OP	F	SED	—	23.1	1,000	27.6	800
Sublette Range #2	..do	E	OH	F	SED	—	20.0	1,250	28.1	600
Tunp #1	..do	E	OP	F	SED	—	23.6	1,000	28.7	700
Tunp #2	..do	E	OP	F	SED	—	24.5	1,000	28.7	800
Tunp #3	..do	E	OH	F	SED	—	22.5	250	33.0	100
Tunp #4	..do	E	OH	F	SED	—	19.8	250	26.0	200

See notes at end of table.

Table A-1.—World phosphate properties included in study—Continued

Country and deposit name	Owner	Status[1]	Mine method[2]	Mill method[3]	Deposit type[4]	Initial production year[5]	Feed grade, wt pct	Mill capacity[6] 10^3 t	Production grade, wt pct	Production capacity[6] 10^3 mt
United States—Continued										
Wyoming—Continued:										
Wyoming Range #1	..do	E	OP	F	SED	—	26.4	1,000	32.2	700
Wyoming Range #2	..do	E	R&P	F	SED	—	21.3	5,000	27.8	3,000
Venezuela: Riecito	Petroquimica de Venezuelá	PP	OP	F	SED	—	26.1	750	31.8	400
Western Sahara: Bou Craa	Governments of Morocco and Spain	P	SL	W	SED	1973	31.5	5,000	36.0	3,000
Zimbabwe: Dorowa	African Explosive and Chemical Industry	P	OP	F	IGN	1965	6.4	1,800	35.0	200

W—Withheld to avoid disclosing company proprietary data.
[1]D—Developing; E—Explored; P—Producer; PP—Past producer; T—Temporary shutdown. Status as of January 1985.
[2]CF—Cut and fill; DR—Dredge; LW—Longwall; OH—Overhand stope; OP—Open pit; R&P—Room and pillar; SL—Strip level.
[3]C—Calcination; F—Flotation; S—Size; W—Wash.
[4]HYD—Hydrothermal; IGN—Igneous; SED—Sedimentary.
[5]Dash indicates no definite startup date or no production as of 1985. Startup date for any developing deposit is based on company projections.
[6]Capacities are either actual or assumed and represent the capacity in the 4th year of production from 1985 (for the producers) or startup (for the nonproducers).

OTHER NORTH AMERICA

The only other significant producing phosphate rock mine in North America is located in Mexico, the San Juan de la Costa Mine, and is owned by ROFOMEX (a Government-controlled company). ROFOMEX is also developing the Santo Domingo deposit and could have it operational by around 1990 if present difficulties are overcome. The La Negra Mine in Mexico is a very small producer and was not included in this study.

There are two phosphate rock prospects in Canada, the Cargill deposit owned by Sherritt Gordon Mines and the Martison Lake deposit owned by Cambell Resources and New Venture Mines. There is interest in developing these mines together, based upon the higher grades of phosphate at Cargill and the significant quantities of recoverable columbium at Martison Lake, although little developmental work has been done.

BRAZIL

Brazil accounts for the only significant production of phosphate rock in South America. Seven mines are operated by six companies in Brazil, and all were included in this study along with four additional explored prospects (most in some developmental stage). Arafertil operates both of the Araxa Mines, while Fosfago de Goias, S.A., Goias Fertilizantes, Serrana, S.A., Fertilizantes Fosfatos, S.A., and Fosfertil, S.A., operate the Catalao-Fosfago, Catalao-Goiasfertil, Jacupiranga, Patos de Minas, and Tapira Mines, respectively. The deposits of Anitapolis, Ipanema, Itataia, and Olinda-Paulista-Igarassu were all included in the study, with Anitapolis' having the greatest potential for further development and capable of being on-stream by 1987.

Nearly all of Brazil's phosphate rock production goes to in-country phosphoric acid plants (except for a small quantity used as direct application material) since Brazil has the intent to be self-sufficient in fertilizer production (and nearly is).

OTHER SOUTH AMERICA

Three other deposits in South America were included in this study: Pesca-Conejera-Sardinata in Colombia (owned by Econimas, a Government-controlled company), Bayovar in Peru (owned by Probayovar, S.A., also a Government-controlled company), and Riecito in Venezuela (owned by Petroquimica de Venezuela). Although small quantities of phosphate rock have, in the past, been produced at both Pesca and Riecito, this study assumes that both deposits are nonproducers and that to attain significant levels of production would necessitate extensive development. Neither is expected to be developed this decade. The Bayovar deposit has had numerous plans for development in recent years and could be operational by the early 1990's if the owner can secure the necessary financing. A small deposit in Antofagasta, Chile, owned by Corfo, was not included in this study.

MOROCCO AND WESTERN SAHARA

Morocco and Western Sahara (whose phosphate rock production is controlled by the Moroccans) represent the largest phosphate rock producers in Africa, third largest in the world next to the United States and the U.S.S.R. All of the mines and deposits in Morocco are owned and operated by the Office Cherifien des Phosphates (OCP), a Government-controlled company. The OCP presently operates 10 mines in Morocco and 1 in Western Sahara (all included in this study).

The Khouribga district, located approximately 140 km southeast of Casablanca, contains five underground operations (all grouped together as one mine for this study) as well as the open pit mines of Daoui (includes Recette-4) and Meraa el Arech. Most of the Khouribga phosphate rock is beneficiated at the various washers and dryers, or at the new dry beneficiation plant in that region. Nearly all Khouribga phosphate rock is used for export from the port in Casablanca.

The Youssoufia district, located 70 km east of the port of Safi, contains four underground operations producing "white" rock and "black" rock (two each), which are grouped into two mines for the purposes of this study. The Youssoufia phosphate rock is beneficiated at the various screening, drying, and calcining plants in the district before being used in Moroccan phosphoric acid plants. The new open pit Ben Guerir Mine (commissioned in 1980), located on the northern edge of the Youssoufia district, was also included in the study. The phosphate rock is screened on-site, then washed in Safi, and is used for phosphoric acid production.

The study also includes nonproducing deposits in both the Khouribga district (Recette-10, Sidi Chennane, and others) and the Youssoufia district (Sidi Hajjaj) as well as the large deposits in the Meskala district. Sidi Chennane and Sidi Hajjaj are the most likely to be developed next, possibly by the early 1990's. Daoui Nord in the Khouribga district (recently mined out) and the open cast mine in the Youssoufia district (recently permanently closed) were not included in the study. The Bou Craa mine in Western Sahara, whose phosphate rock is used by the OCP for export, was also included in the study. Because of the political instability of the region, this mine has frequently been shut down since its opening in 1973, although it is presently producing significant quantities of phosphate rock.

OTHER AFRICA

Tunisia is also a significant producer of phosphate rock in north Africa. There are eight producing mines in Tunisia, all owned and operated by the Government-controlled company, CIE des Phosphates de Gafsa (all are included in this study). Except for one open pit mine, Kef Eschfair, all the producers are underground operations. Their names are Kalaa Khasba, M'Dilla, M'Rata, Metlaoui, Moulares, Redeyef, and Sehib. The nonproducing deposits of Djellabia, Kef Eddour, Oum El Khecheb, and Sra Ouertane were also included in the study. All four are planned open pit mines that could be developed by the late 1980's or early 1990's. Tunisian phosphate rock is both exported and used in the domestic fertilizer industry.

The only mine in Algeria included in this study is Djebel Onk, owned by SONAREM, a Government-controlled company. All its phosphate rock is exported.

The countries of Togo and Senegal in Western Africa are significant producers of phosphate rock (most of which is exported). In Senegal the study included the Government-controlled operations of Pallo (Theis) and Tiaba-Tobene. In Togo, the study included the Government-controlled

Hahotoe-Kpogame Mine as well as the Government-controlled Dagbati deposit, which, if it receives the necessary financing, could be developed by the early 1990's.

Other African mines and deposits included in this study are the Lacunga River deposit in Angola, the South African Palabora Mine (owned and operated by Foskor—the Phosphate Development Co.), the developing Sukulu Hills deposit in Uganda (owned by Sukulu Mines Ltd.), and the Dorowa Mine in Zimbabwe (owned and operated by the African Explosive and Chemical Industry). Development of the Sukula Hills columbium-phosphate deposit in Uganda will be primarily determined by the market for columbium, which will be the principal source of revenue.

Not included in the study are the Tilemsi prospect in Mali, the Glenover and Langbaan Mines in the Republic of South Africa (both very small), the Minjingu prospect in Tanzania, plus the small prospects in Upper Volta and Zambia. Very little information is publicly available on these deposits, and they appear to be quite small in relation to current world standards. They are also small enough to be excluded based on the criteria for deposit selection that are explained in the availability methodology section in appendix D.

ISRAEL AND JORDAN

Phosphate rock production from Middle Eastern countries has become more prevalent in recent years, particularly from Israel and Jordan. Israel has three producing mines, Arad, Nahal Zin, and Oron, all owned and operated by Negev Phosphates Ltd., a Government-controlled company. All three are included in this study, as well as the Beersheba deposit, which is also owned by Negev Phosphates. Beersheba is in early developmental stages and could be in production by the early 1990's. The recently mined-out Maktesh deposit was not included in this study. Two producing mines in Jordan were included in this study, the El Hasa and El Abiad Mines (combined as one) and the Ruseifa Mine. These mines, as well as the developing Esh Shidiyah deposit, are owned and operated by the Jordan Phosphate Mining Co. (Government controlled). Esh Shidiyah is planned to be on-stream by the late 1980's. Most phosphate rock mined in Israel and Jordan is exported.

EGYPT

Egypt is also a significant Middle Eastern phosphate rock producer, although most of its production is used for internal domestic markets (both fertilizer production and direct application material). There are five producing phosphate rock mines owned by three companies in Egypt (all are included in the study). The Abu Zaabel Fertilizer Chemical Co. owns and operates the East and West Sabaiya Mines, and the Red Sea Phosphate Co. owns and operates the Quseir and Safaga Mines. Hamrawein is owned and operated by Misr Phosphates. Only one nonproducing Egyptian deposit was included in the study. The Abu Tartur deposit, owned by the Egyptian Government, has over the years undergone various stages of preliminary development. Because of its remoteness and high estimated costs of production, this mine may not be developed for many years.

OTHER MIDDLE EAST

Other producing mines in the Middle East included in this study are the Akashat mine in Iraq (Government owned), Syria's Kneifess, Sharkya A, and Sharkya B Mines (all three owned and operated by General Co. for Phosphates (Gecopham), a state-controlled agency), and the Mardin (Mazidag) mine in Turkey (owned by Etibank, a Government-controlled company). The West Thaniyat deposit (Government owned) in Saudi Arabia is the only other Middle Eastern nonproducer included in the study. Undeveloped deposits in the Middle East not included in the study are Turayf in Saudi Arabia and the Syrian deposits of Al Haberi and Wadi al Rakheime. Resources at these deposits can be classified only as "inferred" based upon the information available.

EUROPE

Only two European mines or deposits were included in the study, both in Finland, the Siilinjarvi Mine (owned and operated by Kemira Oy—a Government-owned company) and the Sokli deposit (owned by Rautaruukki Oy). No real development has taken place at Sokli. Small deposits in Greece and Yugoslavia were not included in this study because of their size and a lack of publicly available data.

ASIA

The only producing Asian phosphate rock mine included in the study is the Jhamarkotra mine in India (owned by Rajasthan State Mines & Minerals, Ltd.). The two developing Hazara mines in Pakistan (Kakul and Lagarban), both owned by Sarhad Development Authority (Government of Pakistan) were also included in this study. Kakul was to be started up in 1986, with Lagarban only a few years after. Also included in the study is the Eppawella deposit of Sri Lanka. That deposit is owned by the Government (SMMDL), and development of it would be undertaken by Agrico Chemical Co. Various small mines and potential prospects located in India were not included in the study because of their size and a lack of publicly available information.

OCEANIA

Two mines in the Oceania region, Nauru (owned and operated by the Nauru Phosphate Corp.) and Christmas Island (owned and operated by the Phosphate Mining Co. of Christmas Island) were included in the study. Most of the phosphate rock produced at these mines supplies fertilizer production in Australia. The Duchess Mine in Australia (owned by Western Mining Corp.) was also included in this study. It has been shut down most of the time since its opening in 1975 primarily because of marketing problems due to impurities in the phosphate rock product and high transportation costs to get it to the market. Other nonproducing deposits in Australia included in the study are D-Tree, Lady Annie and Lady Jane, Laverton, and various northern Queensland deposits (grouped together as one deposit for the study).

APPENDIX B.—ACID AND FERTILIZER PLANTS INCLUDED IN NETWORK[1]

Country and location	Company	Associated port
Algeria: Annaba	SONATRACH	Annaba.
Australia:		
Greelong	PIVOT	Melbourne.
Kooragang Is.	Australian Fertilizer	Brisbane.
Kwinana	CSBP and Farmers	Perth.
Pinkenba	Consolidated Fertilizer	Brisbane.
Yarraville	ICI Australia	Do.
Austria:		
Linz	Chimie Linz	Rotterdam.
Pischelsdorf	Donan Chemie	Do.
Bangladesh: Chittagong	Bangladesh Development	Chittagong.
Belgium:		
Engis	Prayon-Rupel (OCP)	Do.
Ostende	BASF	Do.
Rieme	Gesa	Do.
Sauvegarde	Prayon-Rupel (OCP)	Do.
Zandvliet	BASF	Do.
Brazil:		
Araxa*	Arafertil	NAp.
Camacari*	Caraiba Metais	NAp.
Cubatao	Copebras	NAp.
Imbituba	Carboquimica	NAp.
Jacupiranga	Quimbrazil	NAp.
Piacaquera	Petroquisa	Belem.
Uberaba	Fosfertil	NAp.
Bulgaria:		
Dmitrovgrad	Bulgarian Government	Burgas.
Povelyanovo (Devnia)	..do	Do.
Canada:		
Alberta:		
Calgary	Western Coop	NAp.
Ft. Saskatchewan	Sherritt Gordon	NAp.
Medicine Hat	Western Coop	NAp.
Red Water	Esso	NAp.
British Columbia:		
Kimberley	Cominco	NAp.
Trail	..do	NAp.
New Brunswick:		
Belledune	Noranda	NAp.
Ontario:		
Courtright	CIL	NAp.
Pt. Maitland	IMC	NAp.
China:		
Guiki*	China Government	Shanghai
Haikou	..do	Do.
Jangxi	..do	Do.
Nanking	..do	Do.
Zhanjang*	..do	Do.
Cyprus: Vasilikos	Hellenic Mining	Vasilikos Bay.
Czechoslovakia: Postorna	Fosfa Postorna	Constanta.
Denmark: Fredericia	Superfos	Do.
Egypt:		
Kafr-El-Zayat	Abu Zaabal	Qusier.
Safaga*	Egyptian Chemical	Do.
Finland:		
Siilinjarvi	Kemira Oy	NAp.
Uusikaupunki	..do	NAp.
France:		
Ambares	Cofaz	Bordeaux.
Bordeaux	Gesa	Do.
Douvrin	APC	Marseilles.
Grande Couronne	..do	Bordeaux.
Le Boucau	Satec	Do.
Do	Socadour	Do.
Le Havre	Cofaz	Do.
Ottmarsheim	APC-BASF	Do.
Roches de Condrieu	Rhone-Poulenc	Marseilles.
Rouen-Grand Quevilly	Gesa	Bordeaux.
Sete	Cofaz	Marseilles.
Wattrelos	PCUK	Bordeaux.
Germany, Federal Republic of:		
Embsen	Chemische Werke Huels	Rotterdam.
Germany, Federal Republic of—Continued		
Knapsack	Hoechst-Werke	Do.
Krefeld	Guano-Werke	Do.
Nordenham	..do	Do.
Greece:		
Drapetsona	Hellenic Chemical Prod	Athens.
Nea Karvali	Phosphatic Fertilizer Industry.	Do.
Thessaloaika	Chemical Industries of Northern Greece.	Do.
India:		
Alwaye	Fertilizer & Chemical Travancore.	Bombay.
Ambernath	Albright-Morarji-Pandix	Do.
Baroda	Gujarat State Fertilizer	Do.
Cochin	Fertilizer & Chemical Travancore.	Do.
Debari	Hindustan Zinc	NAp.
Ennore	EID Parry	Vishakhapatnam.
Haldia*	Hindustan Fertilizer	Bombay.
Do	Hindustan Lever	Do.
Khetri	Hindustan Copper	NAp.
Paradeep*	Paradeep Phosphates	Bombay.
Sindri	Fertilizer Corp. of India	Do.
Trombay	Rashtriya Chemical & Fertilizer.	Do.
Tuticorin	Southern Petrochemicals	Vishakhapatnam.
Vishakhapatnam	Coromandel Fertilizers	Do.
Indonesia: Gresik*	Petrokimia	Surabaya.
Iran: Bandar Khomeini	Khomeini Chemicals	Abadan.
Iraq: Al Qaim	Iraq Ministry of Industry	NAp.
Israel:		
Arad	Negev Phosphates	Port Ashdod.
Do	Rotem Fertilizers	Do.
Haifa	Fertilizer & Chemical	Do.
Do	Haifa Chemicals	Do.
Italy:		
Crotone	Aussidet	Crotone.
Gela	ISAF	Do.
Porto Marghera	Aussidet	Venice.
Do	Fertimont (Montedison)	Do.
Japan:		
Akita	COOP Chemical	Niigata.
Befu	Taki Fertilizer	Yokohama.
Chiba	Asahi Glass	Do.
Goi	Nihon Rinsan	Do.
Hachinohe	COOP Chemical	Do.
Hiroshima	Toyo Rinsan	Hiroshima.
Hokkaido	Mitsui Toatsu	Yokohama.
Kurosaki	Mitsubishi Chemical	Niigata.
Minamata	Chisso	Hiro.
Miyako	COOP Chemical	Yokohama.
Nanyo	Toyo Soda	Do..
Niigata	COOP Chemical	Niigata.
Onahama	Nippon Kasei	Yokohama.
Toyama	Nissan Chemical	Niigata.
Ube	Central Glass	Do..
Do	Ube Industries	Do..
Jordan: Aqaba	Jordan Fertilizer Industry	Aqaba.
Korea, Republic of:		
Chin Hae	Chin Haee Chemical	Pusan.
Ulsan	Yong Nam Chemical	Do.
Yosu	Namhae Chemical	Do.
Lebanon: Selaata	Lebanon Chemical	NAp.
Mexico:		
Coatzacoalcos	Fertimex	Vera Cruz.
Guadalajara	Ind. Quimicas	NAp.
Lazaro Cardenas*	Fertimex	NAp.
Minatitlan	do	NAp.
Monclova	do	Tampico
Pajaritos	do	NAp.
Morocco:		
Jorf Lasfar*	OCP (Maroc Phosphore III)	Casablanca
Do	OCP (Maroc Phosphore IV)	Do.

See notes at end of table.

ACID AND FERTILIZER PLANTS INCLUDED IN NETWORK[1]—Continued

Country and location	Company	Associated port
Morocco—Continued:		
Nador*	OCP (Maroc Phosphore V)	Do.
Safi	OCP (Maroc Chemie I)	Do.
Do	OCP (Maroc Chemie II)	Do.
Do	OCP (Maroc Phosphore I)	Do.
Do	OCP (Maroc Phosphore II)	Do.
Netherlands:		
Pernis	UKF	Rotterdam
Sas Van-Ghent	NV Znd Chemie	Do.
Vlaardingen	Windmill-Holland I	Do.
Do	Windmill-Holland II	Do.
Pakistan: Hazara*	National Fertilizer	Karachi.
Peru: Bayovar*	Probayovar	Lima.
Philippines:		
Isabel*	Philphos Fertilizer	Manilla
Limay	Planters Products	Do.
Toledo	Atlas Fertilizer	Do.
Poland:		
Gdansk	Polish Government	Gdansk.
Krakow	..do	Do.
Szczecin (Police I & II)	..do	Do.
Wizow	..do	Do.
Portugal:		
Barreiro	Quimigal	Lisbon.
Setubal	SAPEC	Do.
Romania:		
Bacau	Romanian Government	Constanta.
Navodari	..do	Do.
Turnu Magurele	..do	Do.
Valea Calugareasca	..do	Do.
Senegal:		
M'Bao	SIES	Dalcar.
Tiaba-Daroj	ICS	Do.
South Africa, Republic of:		
Modderfontein	Triomf Fertilizer and Chemicals.	Richard's Bay.
Phalaborwa	Sentrachem	Do.
Pochefstroom	Triomf Fertilizer and Chemicals.	Do.
Richard's Bay	..do	Do.
Rustenburg	Omnia Phosphates	Do.
Somerset West	Triomf Fertilizer and Chemicals.	Do.
Spain:		
Huelva	Fertiberia	Huelva.
Do	FESA	Do.
Do	Foret	Do.
Sri Lanka: Trincomalee*	Eppawala Phosphates	Trincomalee.
Sweden:		
Halgingborg	Boliden KGMI	Malmo.
Landskrona	Supra	Do.
Syria: Homs	Syrian Government	Tartous.
Taiwan:		
Kaohsiung	China Phosphate	Kaoshiung.
Do	Taiwan Fertilizer	Do.
Tanzania: Tanga	Tanzania Fertilizer	Zanzibar.
Togo: Lome*	Soc. Togolaise d'Engraing.	Kpeme.
Tunisia:		
Gabes	ICM I-III	Gabes.
Do	SAEPA	Do.
Gafsa*	IOG	Do.
Sfax	Siape (A)	Do.
Do	Siape (B)	Do.
Turkey:		
Bandirma	Iskur	Istanbul.
Eladig	Azot Sanayii	Do.
Iskenderun	Gubre Fabrikalari	Do.
Mersin	Akdeniz Gubre Sanayii	Mersin.
Yarimca-Izmit	Gubre Fabrikalari	Istanbul.
U.S.S.R.:		
Amalyk	U.S.S.R. Government	NAp.
Balakovo	..do	NAp.
Byelorechensk	..do	NAp.
Chardzou	..do	NAp.
Cherepovets	..do	NAp.
Dzhambul	..do	NAp.
Gomel	..do	NAp.
Kedainai	..do	NAp.
Kingisepp	..do	NAp.
Konstantinovka	..do	NAp.
Krasnouralsk	..do	Murmansk.
Krym	..do	NAp.
Melenz	..do	NAp.
Revda	..do	Murmansk.
Rozdol	..do	NAp.
Samarkand	..do	Murmansk.
Sumy	..do	Do.
Uvarovo	..do	Do.
Volkhov	..do	Do.
Voskresensk	..do	NAp.
United Kingdom:		
Aberdeen	SAI	Liverpool.
Belfast	Richardson's Fertilizer	Do.
Billingham	ICI	Do.
Immingham	Norsk Hydro	Do.
Leith	SAI	Do.
Severnside	ICI	Do.
Whitehaven	Albright & Wilson I	Do.
Do	Albright & Wilson II	Do.
United States:		
California:		
Helm	Simplot	NAp.
Lathrop	..do	NAp.
Florida:		
Bartow	CF	Tampa.
Do	Grace	Do.
Do	USSAC-Grace	Do.
Ft. Meade	USSAC	Do.
Do	USSAC-Grace	Do.
Mulberry	IMC	Do.
Do	Royster	Do.
New Wales	IMC	Do.
Nichols	Conserv.	Do.
Pierce	Agrico	Do.
Do	Farmland	Do.
Piny Point	AMAX	Do.
Plant City	CF	Do.
Suwannee River	Occidental	Jacksonville.
Swift Creek	..do	Do.
Tampa	Gardinier	Tampa.
Idaho:		
Conda	Beker	NAp.
Pocatello	Simplot	Seattle.
Illinois:		
Depue	Mobil	NAp.
Joliet	Olin	NAp.
Louisiana:		
Donaldsonville	Agrico	Tampa.
Geismar	Allied	Do.
Taft	Beker	Do.
Uncle Sam	Freeport	Do.
Mississippi: Pascagoula	Mississippi Chemicals	Do.
North Carolina:		
Aurora*	NCPC	Morehead City.
Lee Creek	Texasgulf	Do.
Texas: Pasadena	Mobil	Tampa.
Utah: Garfield	Chevron	Seattle.
Wyoming: Rock Springs*	..do	NAp.
Venezuela: Puerto Moron	Tripoliven	Caracas.
Vietnam: Haiphong*	Vietnam Government	NAp.
Yugoslavia:		
Hrastnik	Tovarna Kem Izdekai	Dubrovnick.
Kosovska Mitrovica	Hemijska Industrija	Do.
Kutina	INA	Do.
Prahovo	Hemijska Industrija	Do.
Sabac	..do	Do.
Subotica	..do	Do.
Titov Veles	..do	Do.
Zimbabwe: Harare	Zimbabwe Phosphate Industry.	Richard's Bay.

NAp Not applicable.

[1] All are assumed producers or presently shut down, unless denoted with asterisk, which indicates planned plant (or presently under construction) as of January 1984. Ownership and status also as of 1984.

APPENDIX C.—PHOSPHATE GEOLOGY, RESOURCES, MINING, AND PROCESSING

GEOLOGY

The element phosphorus is widely abundant in the Earth's crust, comprising approximately 0.11 pct. Phosphate (phosphorus pentoxide P_2O_5) concentrations exist throughout the world in both igneous and sedimentary rocks, primarily in the form of the mineral apatite. In igneous rocks, it is generally as fluorapatite, $Ca_5(PO_4)_3F$, and in sedimentary rocks, generally as hydroxy fluorapatite, $Ca_5(PO_4)_3OH,F$, or as carboxyapatite, $Ca_5(PO_4, CO_3OH)_3F$.

The majority of the phosphate resources throughout the world are classified as sedimentary marine phosphorite deposits. The two most significant types are deposits formed in areas of upwelling water and those formed in warm climates, particularly along eastern coasts. The Cretaceous and Eocene deposits of western and northern Africa and the Middle East as well as the Permian Phosphoria Formation of the Western United States are the best examples of deposits formed as a result of upwelling waters. These deposits were formed by chemical and biological precipitation of phosphate in areas of upwelling, phosphate-rich marine waters. The phosphate ore typically occurs in thin, marine sediment sequences in these deposits, and the phosphate itself is typically carbonaceous, consisting of pellets and nodules. The Miocene deposits along the southeastern coast of the United States are the best examples of deposits formed in warm climates. These deposits are economically minable if they have been reworked by submarine currents and/or subjected to weathering (as in the Southeast United States). The phosphate ore typically consists of loose, poorly consolidated phosphatic sands, and soft calcareous clays, marls, etc.

In igneous rocks, apatite usually occurs as intrusive masses or sheets, as hydrothermal veins or disseminated replacements, as marginal differentiations, or as pegmatites. Intrusive masses are the most common occurrence of igneous apatite, usually associated with alkaline igneous rocks including carbonatite, ijolite, nepheline syenite, and pyroxenite. Examples of these types of deposits are in the Kola Peninsula in the U.S.S.R., the Palabora complex in the Republic of South Africa, and the carbonatites of southern Brazil.

A final type of phosphate deposit is the island phosphate deposit, which is formed through the large accumulation of guano from sea birds. The composition of these deposits varies with the degree of leaching by surface waters. Decomposed guano is primarily calcium phosphates. The deposits on Nauru and Christmas Islands in the Pacific and Indian Oceans, respectively, are the best examples of guano deposits. A more detailed description of world phosphate deposit geology is contained in Bureau IC 8989, "Phosphate Rock Availability—World"(*1*).[1]

RESOURCES

Demonstrated world resources in terms of recoverable phosphate rock are estimated to be nearly 36.6 billion mt (table C-1 and figure C-1). North Africa has an enormous

[1] Italicized numbers in parentheses refer to items in the list of references preceding appendix A.

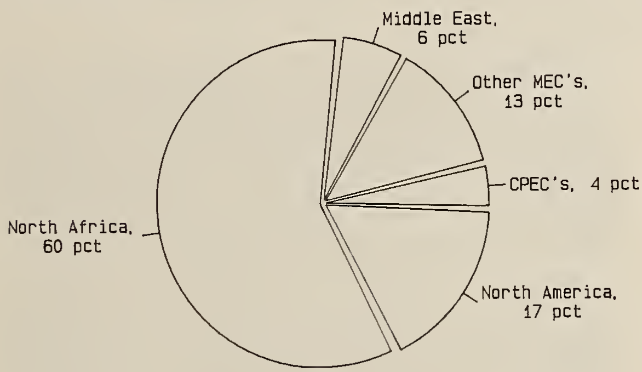
Table C-1.—Summary of world demonstrated phosphate resources as of January 1985

Region and country	In situ ore tonnage, 10^6 mt	In situ grade, wt pct P_2O_5	Recoverable rock product, 10^6 mt	Rock product grade, wt pct P_2O_5
MEC's:				
North America:				
Canada and Mexico	(1)	(1)	199	34
United States	26,625	9	6,104	30
Total			6,303	..
South America:				
Brazil	(1)	(1)	387	34
Colombia, Peru, and Venezuela	2,613	10	415	30
Total			802	..
East Africa: Uganda	186	12	35	42
North Africa:				
Algeria and Tunisia	1,247	22	545	31
Morocco and Western Sahara	39,005	28	21,559	31
Total			22,104	..
Southern Africa:				
Angola and Zimbabwe	39	16	11	34
Republic of South Africa	21,426	6	2,544	37
Total			2,555	..
West Africa:				
Senegal and Togo	834	27	237	34
MEC's—Continued				
Middle East:				
Egypt	1,755	26	1,006	28
Iraq, Saudi Arabia, and Turkey	739	21	304	32
Israel	357	26	190	32
Jordan	1,169	26	511	33
Syria	447	24	204	30
Total			2,215	..
Oceania:				
Australia and Christmas Island	1,588	18	611	33
Nauru	22	38	14	39
Total			625	..
Europe: Finland	1,120	6	114	37
Asia: India, Pakistan and Sri Lanka	107	25	65	32
Total MEC's			35,055	..
CPEC's:[2]				
China	337	26	208	28
U.S.S.R.	(1)	(1)	1,333	33
Total CPEC's			1,541	..
Total world			36,596	..

[1]In situ tonnage and grades are not totaled or averaged because deposits of different geologic types have been combined (e.g., igneous and sedimentary).
[2]Values have not been updated from previous world study; they remain as of Jan. 1981.

phosphate rock resource (22 billion mt), accounting for approximately 60 pct of the total demonstrated phosphate rock resource estimated for the world. The United States is a distant second, with 6.1 billion mt of demonstrated phosphate rock resources, which is over 17 pct of the total. Demonstrated resources for the CPEC's account for only 4 pct of the total. This is more a reflection of a lack of data for these countries than a lack of actual resources.

On the basis of geologic type, sedimentary deposits contain nearly 90 pct of the total demonstrated phosphate rock resource. Significant igneous deposits, which account for the remaining demonstrated resources, are located in Canada, Brazil, the Republic of South Africa, Finland, and the U.S.S.R.



TOTAL RESOURCES, 36.596 X 10^9 mt

FIGURE C-1. — Demonstrated phosphate rock resources, by region, January 1985.

Additionally, the United States has an estimated 7 billion mt of inferred phosphate rock resources. The total inferred resources for all MEC's are over 20 billion mt.

MINING METHODS

Over three-quarters of the phosphate rock produced in MEC's today is recovered by surface mining methods. The remainder is recovered by underground mining techniques, predominantly in Morocco and Tunisia. Table A-1 in appendix A shows individual deposit data such as mining and milling methods, status, capacity, grade, deposit type, ownership, and initial year of production for the deposits and mines included in this study.

The two major surface mining methods used in the phosphate industry are strip level mining and open pit mining. A third method, dredging, is used in special situations.

Strip level mining is the predominant mining method used because of the tabular, bedded, sedimentary nature of most phosphate deposits. In this method, the overburden is stripped from an initial cut and stockpiled. The phosphate ore is excavated while a second, parallel cut is being stripped of overburden. The waste from the second cut is side-cast into the first cut. This cycle is repeated as the mining proceeds.

Ore is removed by a dragline, scraper, or shovel-truck operation. In Florida, draglines dump the ore into a slurry pit where the phosphate material is slurried and pumped through pipes to the beneficiation plant. Most phosphate ore or overburden requires little or no drilling or blasting prior to excavation. Ore in north Africa is a notable exception to this, and blasting is frequently required to mine Moroccan deposits.

Open pit mining is typically employed to recover hard igneous carbonatite rock. The method differs from strip mining in that the waste is stored separately instead of being dumped into mined-out areas. Benching of the waste and ore is often necessary owing to the thickness or depth of the ore. Drilling and blasting are more common in open pit mining than in strip mining.

Dredging is employed at a few deposits throughout the world. It is generally used in special hydrologic situations in which the overburden and phosphate horizon are unconsolidated clay and sand. The Wingate Creek Mine in Florida (United States) is a dredging operation, as will be the proposed Santo Domingo operation in Mexico. Texasgulf Chemical Corp., North Carolina, uses a dredge to remove overburden at its Lee Creek Mine. Pumps dewater the pit, and draglines mine the ore from a bench.

The relatively low unit value of phosphate rock makes underground mining methods generally unprofitable. However, steeply dipping phosphate beds or high stripping ratios sometimes make the use of underground mining techniques preferable. In such cases, highly mechanized room-and-pillar, longwall caving, and overhand-stoping methods have been used successfully. The majority of producing underground phosphate mines are located in northern Africa.

BENEFICIATION METHODS

In almost all cases, the run-of-mine phosphate material has to be beneficiated. The basic beneficiation methods employed in the phosphate industry are sizing, washing, flotation, and calcining. A phosphate beneficiation plant may use one or more of these methods to produce a marketable product.

Average feed grade, average product grade, and average mill recovery are shown in table C-2 for the various MEC regions. Feed grade is here defined as the recoverable grade of the ore that feeds the mill. As shown in this table, the southeast U.S. producers have the second lowest average feed grade but the highest average recovery (at 10.9 pct P_2O_5 and 79.0 pct, respectively). The high recovery results from the use of flotation for most of the material beneficiated. Northern African producers, on the other hand, have an average feed grade of 26.0 pct P_2O_5 and a mill recovery of only 69.8 pct because of losses of fine material during washing.

To reduce long-distance transportation costs, it is important to remove as much water from the phosphate rock as possible by drying. Phosphate rock also must be dried if the grinding circuit (usually located at a phosphoric acid plant) is designed for dry phosphate rock. Many grinding and phosphoric acid plants will now accept wet phosphate rock. Either rotary dryers or fluid-bed dryers are used to dry the phosphate rock. The dry phosphate rock is stored in silos or bins until shipped.

Some operations calcine rock to remove organic matter, which often causes problems with acid manufacture. Many of the operations in Idaho and Morocco use calcining.

Table C-2.—Phosphate mill plant operating parameters, by region[1]

Region	Producing mines			Nonproducing mines		
	Feed grade, pct P_2O_5	Product grade, pct P_2O_5	Recovery, pct	Feed grade, pct P_2O_5	Product grade, pct P_2O_5	Recovery, pct
North America:						
Southeast United States	10.9	30.4	79.0	5.7	30.5	79.6
West United States	22.2	31.2	71.3	21.3	27.7	80.9
South America	9.6	33.8	58.6	9.1	31.8	69.9
North Africa	26.0	32.2	69.8	24.5	31.5	67.4
West Africa	27.1	33.3	40.5	W	W	W
Middle East	24.7	31.4	71.4	24.9	32.6	64.3
Australia	W	W	W	17.5	34.0	86.5

W Withheld to avoid disclosing individual deposit data.
[1]Feed grade, product grade, and recovery are weighted averages for all deposits in each region.

BYPRODUCTS AND DELETERIOUS MATERIALS

Byproducts

Phosphate rock contains several materials that, in most cases, are either very expensive to extract as marketable byproducts or are considered waste products with little or no market value. The most significant of these potential byproducts are uranium (in the form of U_3O_8), recovered from phosphoric acid, vanadium (as V_2O_5), removed from ferrophosphorus, and fluorine (F). Gypsum ($CaSO_4.2H_2O$) is a waste product from the production of phosphoric acid. Few world operations are recovering byproducts from phosphate rock. This study considered byproducts only at operations in which the recovery of a byproduct significantly impacted upon the economics of the entire operation. The following is a discussion of each byproduct's present extraction process, the potential uses for the byproduct, and the constraints presently inhibiting their recovery.

Uranium is the most important byproduct (or potential byproduct) of phosphate. Most phosphate rock contains uranium, although not generally in quantities great enough for economic extraction. On the average, approximately 1 mt of 100-pct-P_2O_5 phosphoric acid will contain 1 lb of recoverable U_3O_8 (*4*).

The process of extracting uranium from phosphoric acid is technologically very complex and is not fully comparable to the extraction of uranium from other kinds of ores. Although some phosphoric acid producers have recovered the uranium (particularly in the Southeast United States), extensive research is presently under way to make this process more economical.

Ferrophosphorus is produced as a byproduct in the production of elemental phosphorus. Ferrophosphorus collected in the electric furnace contains vanadium as well as other metal impurities. It is often sold for the purpose of extracting vanadium pentoxide. However, the supply of ferrophosphorus is greater than the demand from vanadium recovery plants (*4*).

The fluorine content in phosphate rock averages between 3 and 4 pct. No concentration of fluorine occurs during production of phosphoric acid. Some fluorine is retained in the gypsum waste, some escapes as a gas, and some remains in the phosphoric acid. The fluorine gas fraction that is recovered as fluosilicic acid represents only about 35 pct of the fluorine in the phosphate rock prior to phosphoric acid production. The principal uses for fluosilicic acid are in water fluoridation and the production of cryolite. The process of recovering fluorine as fluosilicic acid is presently being used by a number of U.S. phosphoric acid producers (*4*).

Phosphogypsum is a waste byproduct from the wet phosphoric acid process. It is precipitated when the phosphate rock is digested with sulfuric acid. Gypsum is normally stockpiled at the phosphoric acid plant, with a small percentage used as fertilizer or as a soil conditioner (land plaster). In the United States, phosphogypsum is not presently competitive for use in construction material nor is it an economical source for sulfur (*4*).

There are a number of other byproducts presently or potentially recoverable from phosphate deposits. These include copper, zircon, precious metals, and vermiculite at the Foskor operation in the Republic of South Africa; titanium, columbium, rare earths, and vermiculite from Brazilian operations; montmorillonite from the Thies Mine in Senegal; and columbium from Martison Lake in Canada and Sukulu Hills in Uganda.

Deleterious Materials

The quality of phosphate rock for phosphoric acid production is affected by the contained amounts of such deleterious materials as magnesium oxide (MgO), iron and aluminum (as Fe_2O_3 and Al_2O_3), calcium (as CaO), chlorine, and others. These impurities can cause problems during the production of phosphoric acids and tend to decrease the profitability of these operations by increasing costs.

The magnesium oxide content is undesirable because highly viscous magnesium phosphate "sludges" can form during the production of phosphoric acids, which can lower the operation's productivity and increase the energy requirements. The magnesium will also precipitate fluorine in the reactor stage of the wet-acid process, which causes plugging of the gypsum filters (*4*). As a rule of thumb, a magnesium oxide content of approximately 1 pct or higher will cause these problems and is typically unacceptable to a phosphoric acid plant.

The iron and aluminum oxide content is also highly undesirable because it too forms viscous sludges and makes the acids "sticky." If the combined iron and aluminum content (also called the I + A content) is greater than 2.5 to 3 pct, these problems occur and often market penalties are added.

The calcium content of the phosphate rock can affect the sulfuric acid requirements of phosphoric acid production. If the CaO-P_2O_5 ratio is greater than 1.6, then excessive sulfuric acid will be required for the acidulation process.

Chlorine can cause excessive corrosion in the phosphate rock processing equipment. A chlorine content greater than 0.2 pct is presently considered undesirable.

Other materials also considered deleterious to the processing of phosphate rock include fluorine (because of air pollution regulations in the United States), organic matter (because greater than 4 to 5 pct CO_2 can cause foaming in phosphoric acid production), and trace metals (which also can cause the precipitation of sludges in acids).

NEW MINING AND BENEFICIATION TECHNOLOGY

The following section briefly discusses several areas of phosphate mining and processing research that, if successful, could permit or enhance phosphate recovery from known depcsits (particularly in the United States) that are currently not economic to exploit. These new processes could increase the phosphate resource potential and strengthen the competitive position of U.S. producers substantially.

In recent years, the Bureau and various phosphate companies in Florida have been researching technologies for beneficiating or processing phosphate rock from deposits containing high amounts of magnesium oxide (MgO). In phosphate rock, an MgO content of 1 pct or more causes problems in the manufacture of phosphatic acids and is therefore unacceptable to phosphoric acid producers. Bureau research has established the feasibility of a technique for removing a portion of the MgO during beneficiation (*23*). Industry researchers have demonstrated heavy-medium separation and flotation techniques for removing MgO during beneficiation (*24*). If any of these new technologies is developed and proven economically feasible, as much as 2 billion mt of phosphate rock (at the identified resource level) in Florida alone could become available.

Two important mining technologies are also being researched in relation to improved phosphate recovery. A technique to recover deep phosphate resources through borehole mining has recently been developed, although it has never been tested on a commercial scale. In addition, mining of offshore phosphate resources has potential, although it has not as yet been developed into a viable economic method. Both of these mining techniques would substantially increase phosphate rock recovery and resource potential.

PHOSPHORIC ACID PRODUCTION METHODS

Most of the phosphate rock produced in the United States and the rest of the world is used to manufacture fertilizer products (phosphoric acids) to be used by the agricultural industry. The various fertilizer products produced from phosphate rock are wet-process phosphoric acids, normal superphosphates, triple superphosphates, monoammonium phosphates, diammonium phosphates, and direct-application ground phosphate rock (phosphate rock that is applied directly to acidic soils in many regions of the world).

The phosphate rock feed for phosphoric acid production is usually dried and ground, although wet phosphate rock has recently become acceptable to some processing plants, particularly in the United States. Calcination of phosphate rock is not usually necessary prior to phosphoric acid production and can be a very costly step if required; however, calcinated feed produces very high quality phosphoric acid (*4*).

The most common fertilizer product is phosphoric acid, produced by the wet process. The principal reaction involved in all wet-process phosphoric acid plants is the digestion by sulfuric acid of tricalcium phosphate, the primary constituent of phosphate ores. This results in the precipitation of gypsum and the formation of phosphoric acid in solution. Most phosphoric acid processes digest the phosphate rock with sulfuric acid, although in Europe there are some processes that utilize nitric acid (*4*).

Merchant-grade phosphoric acid is one of the most common products from a wet-process phosphoric acid plant. It has been more prevalent in recent years because it has a low content of impurities. Therefore, the phosphoric acid can be shipped without large amounts of precipitated solids.

APPENDIX D.—AVAILABILITY METHODOLOGY

A total of 206 mines and deposits were evaluated (124 domestic and 82 foreign). These deposits include resources of phosphate rock at the demonstrated level that can be mined and milled using current technology. Mines and deposits in the U.S.S.R. and China were not included in the availability analysis owing to the difficulty of gathering accurate cost data and converting them to U.S. dollar equivalents.

Typically, beneficiated phosphate rock contains 7 to 20 pct moisture. Many processes that convert phosphate rock into its numerous end products will accept wet phosphate rock feed, although less than 3 pct moisture is desirable. The final product in the availability study is defined as *dry* phosphate rock. For this study, the term "phosphate rock" refers to the beneficiated product, and "phosphate ore" refers to the minable material in the ground.

For purposes of consistency, it was assumed in the evaluation that all phosphate rock produced at a mine was transported to a local port for export unless that phosphate rock was being used for internal domestic consumption. If internally consumed, the phosphate rock was transported to a nearby phosphoric acid plant or market. Table D-1 lists the destination points assumed for the availability study. Additional costs for further processing of phosphate rock into its many end products were not included in the availability analysis. Phosphoric acid plant costs and additional transportation costs enter into the solution of the network flow model discussed in the "Supply" section and appendix E.

The analysis methodology of the availability study is as follows:

1. The quantity and grade of phosphate ore resources were evaluated in relation to physical and technical conditions that affect production from each deposit as of the base date, January 1985.

2. The capital investments and operating costs for appropriate mining, concentrating, and processing methods were estimated for each mine or deposit. Company-provided data were used when possible, but many of the cost and operating parameters were estimated using available information, supplemented by the Bureau's cost estimating system (CES) (*15*).[1]

3. A cash-flow analysis of each operation determined the total cost (or average revenue requirement per metric ton of phosphate rock) determined over its entire producing life (as determined by estimates of capacity and demonstrated resources) and the associated total demonstrated tonnage of phosphate rock product that could potentially be recovered at specific production levels.

4. Upon completion of the individual property analyses, all properties included in the study were simultaneously analyzed and sequentially aggregated onto phosphate rock availability curves. These curves are of two types. Total availability curves are aggregations of total potential phosphate rock that could be produced over the life of each operation, ordered from the lowest cost deposits to the highest. Annual availability curves are aggregations of potential phosphate rock production capacity within a single year, also ordered from lowest cost deposits to highest. Annual curves reflect current or expected levels of installed capacity at each operation.

[1] Italicized numbers in parentheses refer to items in the list of references preceding appendix A.

Table D-1.—Assumed destinations for phosphate rock, by country

Country	Market[1]	Location of port or acid plant
North America:		
Canada	IC	Port Maitland.
United States:		
Florida	E	Tampa or Jacksonville.
Idaho	IC	Pocatello or Soda Springs, ID; Silverbow, MT.
Montana	IC	British Columbia.
North Carolina	E	Morehead City, NC.
Tennessee	IC	Mt. Pleasant.
Utah	IC	Pocatello or Soda Springs, ID; Rock Springs, WY.
Wyoming	IC	Pocatello or Soda Springs, ID.
Mexico	IC	Port Belcher or Lazaro Cardenas.
South America:		
Brazil	IC	Uberaba, Santos, Imbituba, Fortaleza, Rio, or Recife.
Colombia	IC	Pesca.
Peru	E	Port Bayovar.
Venezuela	IC	Moron.
North Africa:		
Algeria	E	Annaba.
Morocco	E	Casablanca, Safi, or Jorf Lasfar.
Tunisia	E	Sfax or Gabes.
Western Sahara	E	El Aaiun.
Other African countries:		
Angola	E	Lacunga River mouth.
Senegal	E	Port Dakar.
South Africa, Republic of	E	Maputo.
Togo	E	Port Kpeme.
Uganda	IC	Tororo.
Zimbabwe	IC	Salisbury.
Middle East:		
Egypt	E	Safaga.
Iraq	E	Khor-Al-Zuber Port.
Israel	E	Port of Ashdad.
Jordan	E	Aquab.
Saudi Arabia	IC	Hagl.
Syria	E	Port Tarfous.
Turkey	IC	Elazig.
Oceania:		
Australia	E	Port at Gulf of Carpentaria or Townsville.
Christmas Island	E	Christmas Island.
Nauru	E	Nauru.
Europe: Finland	E	Leningrad or port in Gulf of Finland.
Asia:		
India	IC	Udaipur.
Pakistan	IC	Failasbad.
Sri Lanka	IC	Trincolmolee.

[1]E—Export; IC—Internal consumption.

The availability curves show the costs associated with any given level of annual or total potential output; i.e., they illustrate the average long-run phosphate rock price that each operation would require in order to provide revenues sufficient to cover the average total cost of production, including a return on investment high enough to attract new capital. The rate of return on investment used in this study is a 15-pct discounted-cash-flow rate of return (DCFROR).

The flow of the Minerals Availabilty Program evaluation process from deposit identification to analysis of availability information is illustrated in figure D-1.

For the deposits analyzed, tonnage estimates were made at the demonstrated resource level based on the mineral resource-reserve classification system developed jointly by the Bureau and the U.S. Geological Survey (*25*). The demonstrated resource category includes measured plus indicated tonnages (fig. D-2).

To be included in the availability analysis, U.S. phosphate deposits had to meet technological criteria representing currently acceptable U.S. industry standards at the time of the analysis. The criteria shown below for

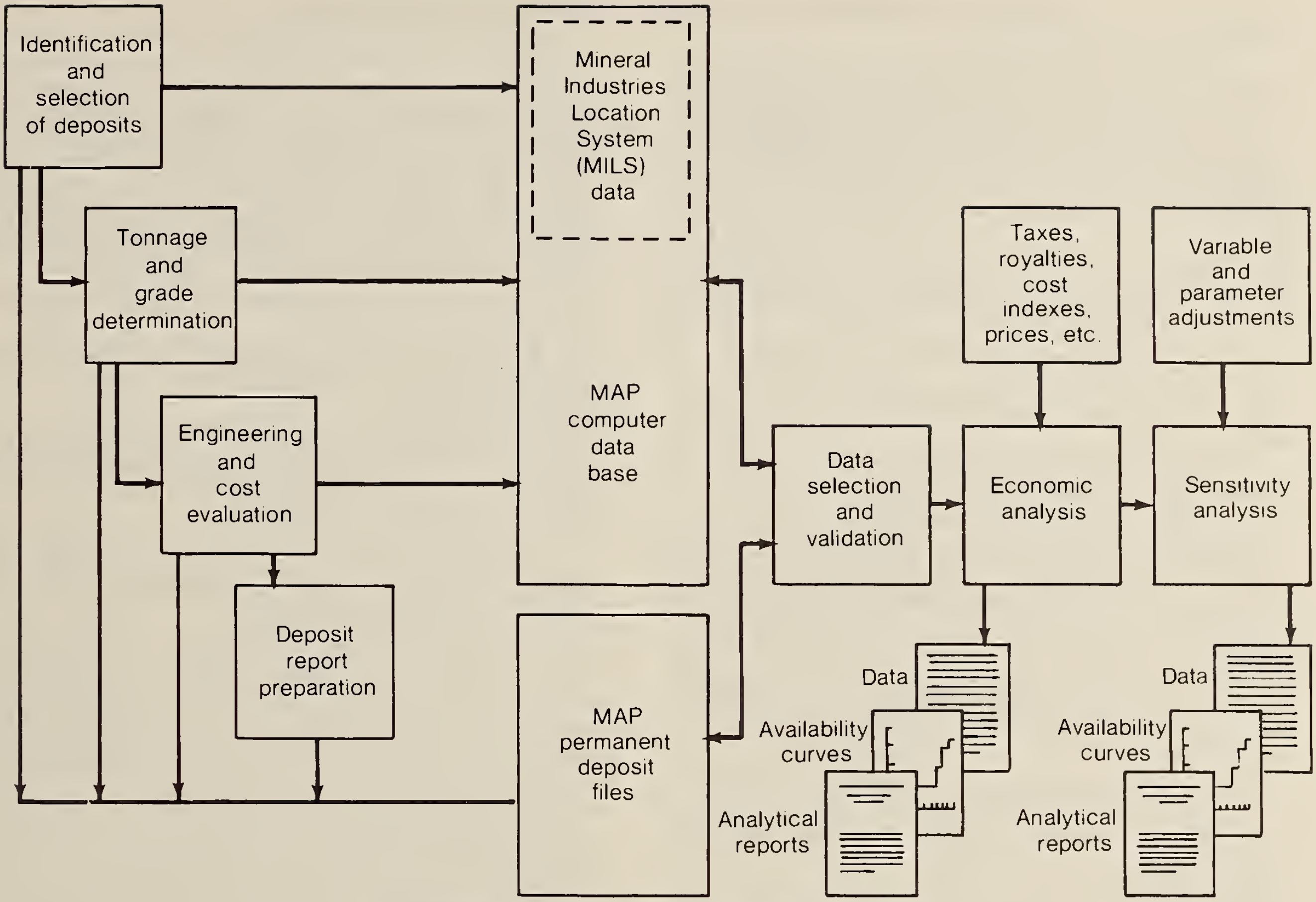


FIGURE D-1. — Flow chart of evaluation procedure.

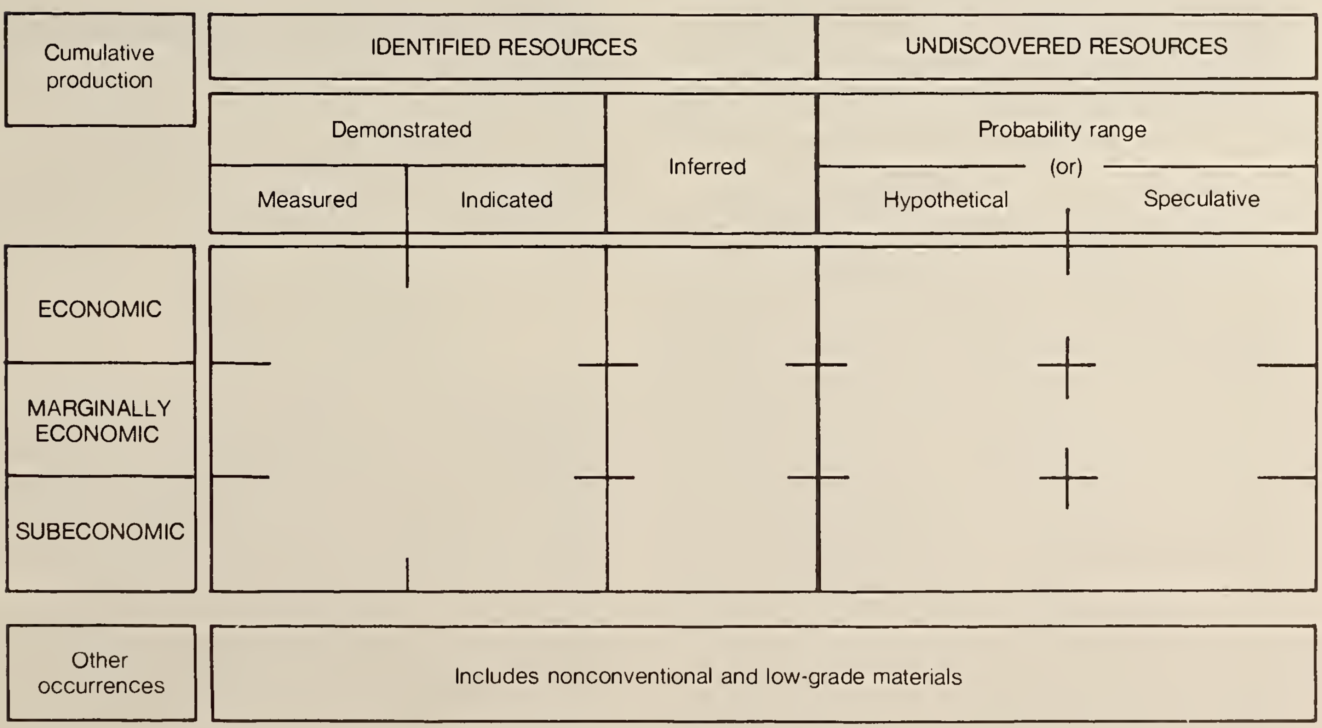


FIGURE D-2. — Mineral resource classification categories.

the Southeast deposits should be viewed as guidelines rather than absolute limits (*26*).

1. Deposit size must be more than 5 million mt of recoverable phosphate rock,[2] and material must be within an average radius of 1.5 miles[3] from center of the ore body.

2. Deposit size must be more than 10 million mt[2] if the average overburden thickness is more than 6 m, and must be within an average radius of 2.5 miles[3] of the ore body centroid.

3. Deposit size must be greater than 15 million mt[2] if the overburden average thickness is more than 9 m, and must be within an average radius of 2.5 miles[3] from the center of the ore body.

4. The flotation feed grade must be more than 4.6 pct P_2O_5.

5. The concentrate grade must be more than 27.5 pct P_2O_5.

6. The phosphate concentration must be at least 1 mt of recoverable product per 8 m^3 of ore.

7. The ore zone must be more than 2 m thick.

8. Phosphate rock product must contain less than 1.5 pct MgO. (Resources of high-MgO phosphate are quantified in this report and technological developments are discussed, but no deposits containing greater than 1 pct MgO were evaluated.)

The following criteria for developing resource estimates of Tennessee phosphate deposits represent ranges that the central Tennessee phosphate companies recognize as representing acceptable minable deposits (*27*).

1. A minimum cutoff grade range of 16 to 17.2 pct P_2O_5.

2. Minimum ore thickness range of 0.6 to 1.2 m.

3. Maximum overburden-to-ore ratio range of 3:1 to 4:1.

4. A minimum ore body size of 22,675 mt (dry) of phosphate rock.

The average ore body in Tennessee is small—150,000 to 1.2 million mt—which means that deposits at a number of separate locations may have to be mined to satisfy one company's annual requirement.

The study criteria for explored deposits in Utah and Wyoming include a minimum ore thickness of 0.91 m and a minimum average grade of 18 pct P_2O_5. For economic classification, minable resources were further subdivided by depth, thickness, dip, grade, and probability of occurrence. Resources above adit-entry level[4] were estimated and economically evaluated after site-specific corrections were applied. The quantity of resources occurring below adit-entry level was not costed or economically evaluated in this study because of the extremely high recovery cost.

The foreign deposits included in the analysis had to meet the following set of criteria:

1. Producing properties accounting for at least 85 pct of the phosphate rock production from each significant world producing country.

2. Developing and explored deposits where the demonstrated phosphate rock reserve-resource quantity was equivalent to at least the lower limits of the reserve-resource quantity of the producing deposits.

3. Past-producing deposits where the remaining demonstrated phosphate rock reserve-resource quantity was equivalent to at least the lower limits of the reserve-resource quantity of the producing deposits.

Evaluation of each phosphate property included determining phosphate resources, deposit development, technologies, and costs. Information on the average grades, ore tonnages, and different physical characteristics affecting production from domestic phosphate deposits was obtained from numerous sources, including Bureau and Geological Survey publications, professional journals, State and industry publications, annual reports, company 10K reports and prospectuses filed with the Securities and Exchange Commission, data made available to the Bureau by private companies (domestic and foreign) or via contract, and estimates made by Bureau personnel based on personal knowledge and judgments.

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[2] Exceptions—if the deposit is adjacent to larger identified deposits or is in hardrock areas.

[3] This radius equates to the resource ore body covering one-half of the area of the deposit, at an average of 2,500 mt per acre.

[4] The adit-entry level is defined as the nearly horizontal access to the minable resource. The adit level also serves as a conduit for natural mine water drainage.

APPENDIX E.—SUPPLY MODELING METHODOLOGIES

This section describes how the data collected for the availability study has been incorporated into two forms of world mineral market models. The two model forms constructed are referred to as the "market balance" and "network flow" models. They are complementary in their capabilities, but each has characteristics that are unique and its own subset of required data items. For the most part, they utilize a common deposit data base and, as much as possible, a common software set.

The modeling tools that have been developed answer different types of policy analysis questions and service different levels of users. The form of the market balance model is a combination of systems dynamics and econometrics. An engineering-based, deposit-specific supply side has been substituted for the usual econometric approach that extrapolates from past information. The network flow model form takes additional advantage of the extensive deposit data base with a unique optimization methodology.

These two distinct tools for analysis can be used independently. The market balance approach is well suited to relatively quick turnaround analysis and can be constructed with a less extensive data base than is required for the network flow approach. The market balance model offers a dynamic solution capability (i.e., it solves for a user-defined series of years) and is best suited to addressing intermediate to long-term issues. The network flow model solves for a single year at a time and is more suited to analysis of short-term issues. It can provide enormous insight into the competitive structure of the market.

A wide range of scenarios can be defined with the current versions of the two forms of phosphate models. For example, the relative competitive positions of alternative future supply sources can be examined. The impacts of various tax, tariff, and subsidy issues can be considered. Capital expenditure issues and property development decisions can be assessed. Disruption analyses can be defined on a property or regional basis. Effects of alternative demand levels can be examined. Effects of changing input costs or changes in market structures can be examined.

The modeling tools offer an analyst access to the deposit data base and place a supply-side representation built from that data base within a world market context. The following sections provide documentation of the market balance model and the network flow model.

MARKET BALANCE

General Description

The market balance model is an engineering-based model that fits the system-simulation or systems-dynamics category of mineral market models and also includes attributes of an econometric model. A system-simulation model typically interconnects submodels, each of which captures generally accepted behavior on a small scale, in an attempt to simulate overall performance on a large scale (*18*).[1]

The submodels that comprise the market balance model framework include all the elements of a standard market-simulation model combined in a logically correct representation of the market. These include supply, demand, and price determination, as well as an iterative balancing procedure for finding an equilibrium solution. The market balance model also provides the user with default values for all the data in the projection period and provides a complete set of definitional or statistically derived behavioral relationships that tie the pieces together. The assumptions and simplifications necessary to construct a working phosphate model tend to define the scope of analysis that can be performed. As a result, a thorough understanding of the entire model form is necessary for interpreting results and defining reasonable scenarios for analysis.

The overall design of the market balance model requires that the estimated amounts of P_2O_5 consumed in fertilizer and nonfertilizer products be equal to the estimated amount supplied to the market at equilibrium. The method for reaching balance is an iterative process that finds a single world price at which the amount supplied and the amount demanded are in balance. Lower prices cause fertilizer demand estimates to increase while higher prices lead to decreases in demand. Supply responds to price in the opposite manner. More deposits produce at a higher price (because more are able to cover their average variable costs), and deposits that are already producing will produce more according to a capacity-utilization equation described later in this section, if they are not already producing at maximum capacity. (The model assumes normally sloped supply and demand curves.)

Figure E-1 shows the phosphate supply-demand model prototype. Solution of supply is a function of deposit and market information coupled with decision rules and takes into account all constraints known to a user and entered into the data base. Solution of demand likewise uses an information set and decision rules and can incorporate user constraints. The balance achieved accounts for product definitions and processing and handling losses.

The software system for using the market balance model is flexible enough to allow users a wide choice of submodels. Demand can be solved with a set of econometric equations for eight world regions, or it can be determined exogenously. Supply can be solved using a choice of behavioral assumptions to define the logic of the supply-side response to price and other market conditions.

Supply from MEC deposits is solved a single year at a time, with the assumption that a competitive world market exists for phosphate rock. That is, all P_2O_5 in phosphate rock is presumed to be of equivalent quality (homogeneous product), there are many sellers of the product, and each firm perceives a fixed world market price that cannot be affected by its production decision. Individual deposit cost functions define the quantity of inputs necessary to produce different levels of output. Optimizing behavior by the firm is to select that level of output at which profits (the difference between revenues and costs) are maximized. Figure E-2 shows curves for average variable costs (AVC), marginal costs (MC), and a hypothetical market price (P_0) to illustrate this concept. The optimum output (Q_0) is shown as the intersection of a horizontal line drawn at the level of the market price (P_0) and the rising portion of the firm's MC curve, i.e., the point where marginal cost equals marginal revenue.

The minimum "point" on the average variable cost curve in figure E-2 is shown as a flat segment, indicating a wide range of possible output over which the per-unit variable cost of phosphate production is the same. This is so because production at levels below rated annual capacity

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[1] Italicized numbers in parentheses refer to items in the list of references preceding appendix A.

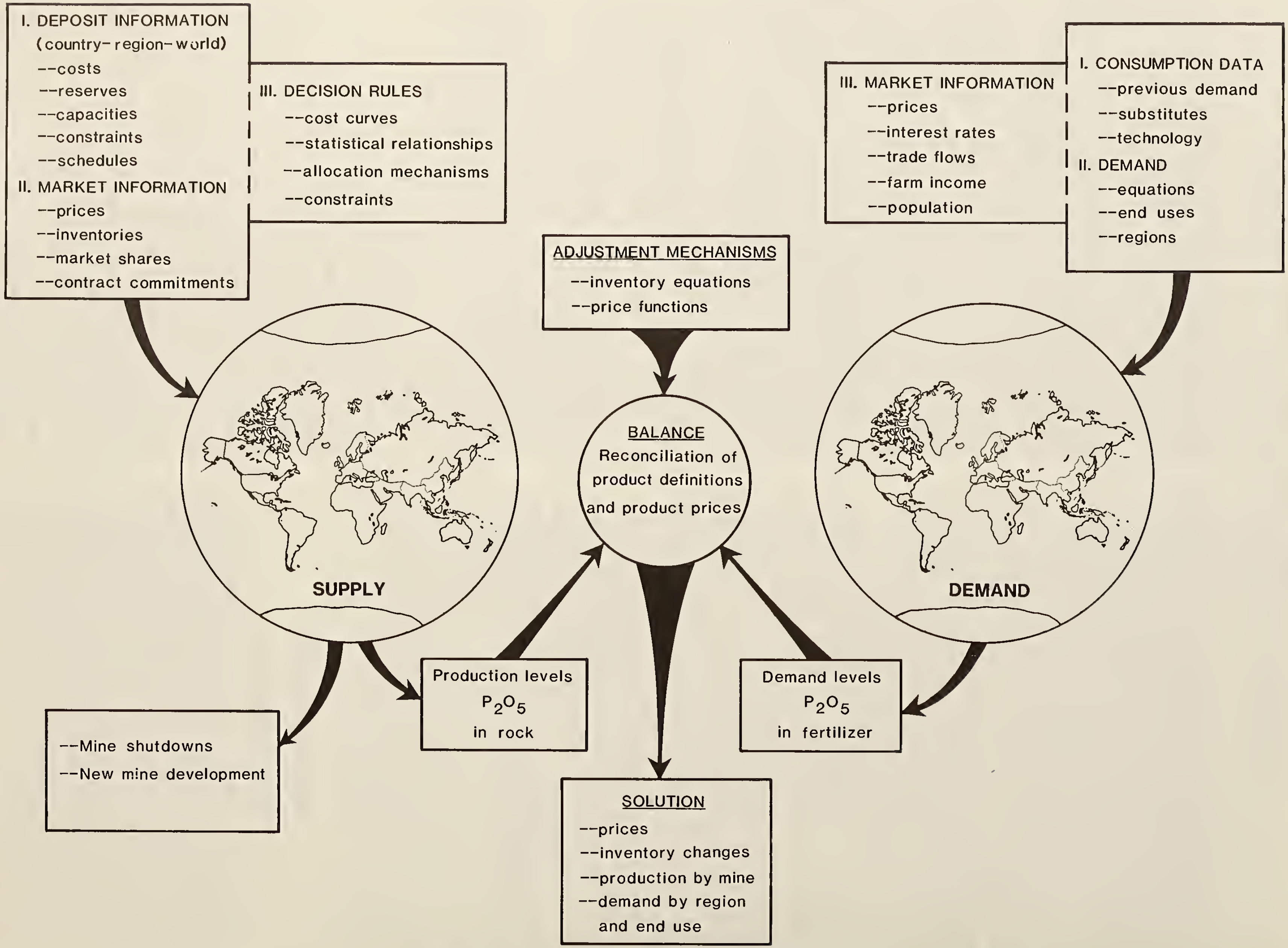

FIGURE E-1. — Prototype of world phosphate balance model.

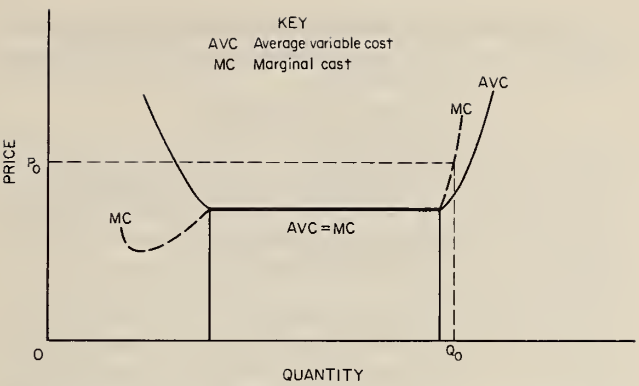

FIGURE E-2. — Truncated marginal and average variable cost curves.

generally means shutting down the operation at regular intervals or for a portion of the year. For example, Florida operations can work a 5-day week or a 7-day week at the same average variable cost level. The cost of opening or closing facilities is small, and maintenance costs during a temporary shutdown are likewise small relative to the average variable cost of production. Many western U.S. properties are not operated during the winter months, and the level of annual output is adjusted by the choice of dates for beginning production in the spring and stopping production in the fall; average variable costs are the same over a wide range of output levels. The upper end of the curve is shown as a near-vertical line, indicating that installed capacity represents an upper limit on total output. Additional output is not forthcoming (in the short term) even if an operator is willing to pay much higher costs.

The implication in the market balance model of this form of deposit supply curve is that a property will either operate at capacity when price is at or above the intersection of AVC and MC, or it will shut down if price is below the minimum of AVC. This curve is referred to as the "definitional" deposit supply curve. Other options available to a model user are to prespecify production levels or to use a capacity-utilization equation described in a later part of this section. The network flow model, described later in this appendix, uses the definitional supply-curve representation, but the existence of multiple markets and the optimization procedure lead to production levels that are below full capacity at many deposits.

Historical production data for U.S. phosphate mines are not entirely consistent with the definitional deposit supply curve. Annual output from different properties tends to rise and fall somewhat in concert with annual average price cycles. The maximum output for most properties has been above rated capacity in one or more recent years. A capacity utilization equation that allows for this pattern of observed production behavior was estimated and incorporated into the market balance model structure as a user option. Results from simulations using this form of supply determination are shown later in this section. These results differ only marginally from results using the definitional supply curve, but the capability to use either form was included in the model for completeness.

Figure E-3 shows a typical supply curve for a single year, as generated by the market balance model. The supply curve in each year is a step function, with the horizontal axis equal to cumulative annual production and the vertical axis equal to price or the average variable production cost. Each step on the curve corresponds to an individual deposit. The representation shown assumes that parameters have been set to simulate the definitional form of the deposit supply curve previously discussed. (A supply curve based upon the capacity-utilization equation is discussed later in this section.)

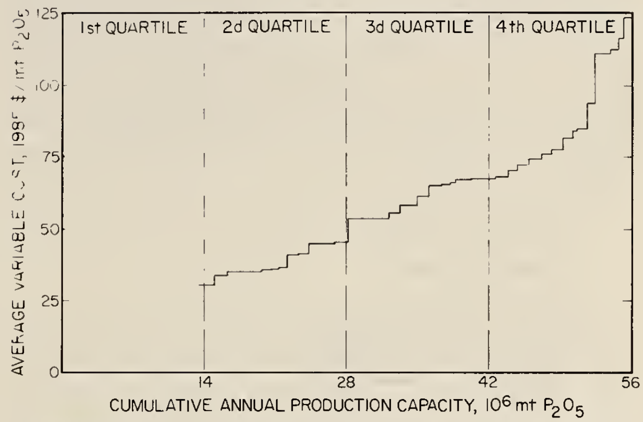

FIGURE E-3. — Typical market balance model MEC supply curve.

Definitions and Assumptions

The definitions and assumptions behind the curves shown in figures E-2 and E-3 are given below. Units of measure are defined, as is the manner in which different variables are calculated for inclusion in the market balance model. Further explanation of how the model variables relate to each other comprises the remainder of this section.

Unit of measure for quantities supplied or demanded is in terms of recoverable units of P_2O_5 in phosphate rock. Simulated values for market price are in terms of constant January 1985 U.S. dollars per unit of recovered P_2O_5 in phosphate rock. Cost measures internal to the market balance model are also January 1985 U.S. dollars, but are applied against the appropriate quantity units for the stage of processing.

Capacity at each MEC deposit is in thousand metric tons of material treated per year. It presumes a normal amount of downtime for routine maintenance and repairs, but generally the maximum possible number of shifts and working days are built into the estimate. Planned expansions that are judged to have a high probability of occurring are built into the data for the years those expansions are expected to take place.

Rate of capacity utilization for each deposit is the proportion of available production capacity utilized in the current year. The utilization factor is determined automatically as a statistically estimated function of costs and a weighted average of current and past prices. Parameters of this function can be set to values that simulate the definitional deposit supply curve.

Capital costs estimated for each deposit in each year were reported in detail in the "Capital Costs" section under "Methodologies." Each capital cost entry is an annual expenditure with a prespecified depreciation schedule. Capital costs are used in the calculation of the DCFROR incentive price, which in turn is used by the model to determine the order in which deposits are developed. They are not part of the variable costs used to make short-term production

decisions. Expenditure items such as land acquisition are treated analogously to capital costs.

Operating costs for each deposit in each year are disaggregated into major components; each cost category can be adjusted separately by the model user, or the entire mine or mill operating cost can be altered. Mine operating costs are applied against material extracted. Mill operating costs are applied against material entering the milling process (same as units extracted in mining process). All operating costs are recomputed in terms of dollars per unit of recovered P_2O_5 in phosphate rock before they are used in the capacity-utilization equation on the supply side of the model. The components of mine and mill operating costs for phosphates are—

Supervisory labor,
Skilled labor,
Unskilled labor,
Electrical power,
Fuel (gas, diesel, etc.),
Supplies (nonenergy),
Equipment repair parts,
Administration and general overhead.

Transportation costs for each deposit in each year include charges for moving material to a port or regional marketing center or to a phosphoric acid plant for further processing.

Severance tax payment levels are determined during simulation and depend on a method of calculation appropriate to each country or State. Payment levels can be a function of the number of units produced or can take account of the selling price for the material. Some foreign properties are built with an assumed fixed payment for severance taxes if the method of calculation cannot be approximated by any of the options available.

Royalty payment levels are also determined during simulation. Payment levels can be made a function of the number of units produced, can take account of the selling price for the material in determining payment levels, or can assume a fixed payment for royalties if the method of calculation cannot be approximated by any of the options available.

Average variable cost for a deposit is the avoidable cost per unit of production; i.e., it is the combination of expenditure items that can be avoided if the operation is not operating. The average variable cost measure is equivalent to marginal cost over a wide output range, as shown earlier in figure E-2. It is, therefore, the relevant short-term cost measure for determining whether or not a deposit will produce under current market conditions, and if producing, the production level. Average variable cost levels for each year for each deposit are currently defined as the sum of per-unit mine operating cost, mill operating cost, transportation cost to a port or processing plant, and those royalty payments and severance taxes that are calculated as a function of the amount or value of material produced. The definition of variable cost used in the phosphate model is

$$VC_i^t = mineop_i^t + millop_i^t + trans_i^t + roy_i^t + sev_i^t$$

where VC_i^t = average variable cost at deposit i in period t, in January 1985 constant U.S. dollars;

$mineop_i^t$ = mine operating costs at deposit i in period t, the summation of the eight mine cost components previously described;

$millop_i^t$ = mill operating costs at deposit i in period t, the summation of the eight cost components;

$trans_i^t$ = transportation cost for moving material from deposit i in period t; all material from MEC deposits is transported to either a transshipment point such as a port or a further processing point such as a phosphoric acid plant;

roy_i^t = royalty payments on production or revenues from deposit i in period t; only those royalty methods that apply a charge against current production levels are considered part of variable cost;

and sev_i^t = severance tax payments on production or revenues from deposit i in period t; only those severance tax methods that apply a charge against current production levels are considered part of variable cost.

Market price (as determined in the model) is an annual average U.S. price per unit of P_2O_5 in phosphate rock. Two other prices are calculated from the U.S. price. These are the Casablanca price of P_2O_5 in phosphate rock (which is used to determine production levels for foreign deposits) and the U.S. gulf price of superphosphate (which is used in the demand equations). Each of these companion prices is set equal to a multiple of the U.S. phosphate rock price, with the multiple equal to the average price differential for the 1964-84 period. Current factors defining the price (P) relationships are

$$P^t_{Casablanca} = 1.4 \bullet P^t_{USrock}$$

$$P^t_{superphos} = 2.0 \bullet P^t_{USrock}.$$

Minimum price required for a deposit to produce is equal to that deposit's average variable (i.e., marginal) cost level. Those developed deposits that cannot cover their variable costs at the market price are presumed to be shut down unless other information indicates that the property would continue to operate because of nonmarket considerations. All U.S. deposits are presumed to face the U.S. price, and all foreign deposits are presumed to face the Casablanca price.

Inventories are held at a constant level throughout the projection period. The user can add to or subtract from current levels by entering the desired inventory change as an exogenous source of supply.

Processing and handling losses in the production and transportation of final products are accounted for with a multiplicative factor on total supply. Even though the processing of phosphate into various fertilizer products is not explicitly represented in the market balance model, the physical losses incurred in those processes must be accounted for when computing the required supply. The factor is applied at the point in the iterative procedure where total demand and total supply are balanced. Between 6 and 11 pct of the P_2O_5 content is lost in the manufacture of phosphoric acid, depending on the technology used. An additional 2 to 5 pct of P_2O_5 can be lost in the production of various forms of fertilizers. Available data for recent years suggest an average 13.1 pct of phosphate rock is lost in processing or handling, and that is the value used in the

model simulation. Recoveries for mining and milling are accounted for separately by factors unique to each deposit.

Supply Determination

Total production (the solution of the supply side) in the market balance model is a summation of simulated production from each of the MEC deposits, plus production from CPEC deposits, plus production from small U.S. and foreign deposits not included in the MEC supply model data base.

Production from MEC deposits is calculated within the model for each year of the simulation as a function of deposit-specific costs and the current and previous period market prices. Price is also estimated each year as part of the model solution.

Production decisions are based on the individual desposit supply curves discussed earlier. Using these curves, the program selects an output level for each producer where marginal cost is equal to market price (i.e., the competitive market level). Using the definitional supply curve described earlier means a choice between full-capacity production and shutdown for each operation.

The average variable cost curves for domestic phosphate properties are truncated U-shaped curves. That is, there is a wide range of possible output levels at each operation where the marginal cost per unit of output is effectively the same (fig. E-2). Capacity represents a physical constraint on output. A willingness to spend more money will not overcome this in the short run (i.e., the deposit supply curve is nearly vertical at capacity). Therefore, the definitional supply curve developed from the estimates of costs at various output levels in a simple form for individual deposits, and the corresponding industry supply curve is a step function (fig. E-3).

The production history of domestic phosphate rock mines clearly shows, however, that most operations vary annual output levels in response to market conditions, and it was decided to supplement the definitional approach to deriving supply curves with an econometric approach. The econometric equation determines a capacity utilization rate as a function of deposit-specific costs, market price, and inventories. The form of that relationship in the simulation model is as follows:

$$CAPUT_i^t = a1 + a2 \bullet (P^t + P^{t-1})/VC_i^t + a3 \bullet I_{US}^t/I_n^t \quad \text{if } VC_i^t < P^t,$$

$$CAPUT_i^t = 0 \quad \text{if } VC_i^t \geqslant P^t,$$

where $CAPUT_i^t$ = capacity utilization rate for deposit i in period t;

a1, a2, a3 = statistically estimated parameters that can be set to unique values for each supply region;

VC_i^t = average variable cost for deposit i in period t;

P^t = simulated U.S. price for P_2O_5 in phosphate rock in period t;

P^{t-1} = previous period's value of P^t;

I_{US}^t = beginning of period t level of U.S. inventories;

and I_n^t = normal level of U.S. inventories calculated as a constant proportion of previous period's production level.

The equation was estimated with inventory as an explanatory variable, but inventories do not appear in the simulation equation. The market balance model simulations done for this study presume inventory change each year to be zero, and the parameter on inventories is subsumed into the constant term of the equation.

Note that the $CAPUT_i^t$ equation reproduces the "definitional" supply curve with a proper choice of parameters. Setting a1 equal to 1.0 and a2 and a3 equal to 0.0 causes the industry supply curve to be that shown in figure E-3. Using the $CAPUT_i^t$ equation and an appropriate choice of the parameters a1, a2, and a3, a simulation value for production is derived as follows:

1. An initial guess at an equilibrium value for the U.S. market price is made automatically by the simulation algorithm. Generally this will be the solution value from the previous time period. An iterative procedure is used to refine the estimate of this period's equilibrium price. The last step in the iteration process is to check to see if equilibrium on price, supply, and demand has been achieved, and if not, to send the computer program back to this step with an adjustment of price for the next iteration. If equilibrium has been found, the program moves to step 2.
2. Production from each of the developed U.S. deposits is predicted. This is done by solving the $CAPUT_i^t$ equation shown previously, with P^t set equal to the value in the current iteration. Multiplying $CAPUT_i^t$ times capacity_i^t yields a simulated value for production in that year for property_i.
3. A value for the Casablanca price of P_2O_5 in phosphate rock is derived as a multiple of the U.S. price. An average multiple of 1.4 was calculated from data for the 1964-83 period, and this value has been incorporated into the market balance model.
4. Production levels for all foreign MEC deposits are calculated in the same fashion as for the U.S. deposits, by solving the $CAPUT_i^t$ equation and multiplying times capacity_i^t.
5. Total production from U.S. and foreign MEC deposits is the summation of all production values derived above.
6. Production from CPEC's and from small deposits in the United States and other MEC's are added to get total world production of P_2O_5 in phosphate rock. Total supply in the market balance model is derived through the set of equations of the following general form:

$$prod_i^t = f(P_{rock}^t, VC_i^t, CAP_i^t),$$

$$prod_i^t \leqslant F_c \bullet CAP_i^t,$$

$$prod_{MEC}^t = \sum prod_i^t,$$

$$prod_{total}^t = prod_{MEC}^t + prod_{U.S.S.R.}^t + prod_{China}^t + prod_{Korea}^t + prod_{Vietnam}^t + prod_{other}^t$$

where $prod_i^t$ = simulated production from deposit i in period t;

$prod_{MEC}^t$ = total production from all 206 MEC deposits in period t;

$prod^t_{U.S.S.R.}$ = production from U.S.S.R. in period t (exogenous);

$prod^t_{China}$ = production from China in period t (exogenous);

$prod^t_{Korea}$ = production from North Korea in period t (exogenous);

$prod^t_{Vietnam}$ = production from Vietnam in period t (exogenous);

$prod^t_{other}$ = production from small MEC deposits in period t (exogenous);

$prod^t_{total}$ = total production of P_2O_5 in phosphate rock in period t;

P^t_{rock} = price of phosphate rock in period t, in constant January 1985 U.S. dollars (there are two rock prices in the model; non-U.S. deposits face the Casablanca price for rock, calculated as a multiple of the U.S. price);

VC^t_i = average variable costs at deposit i in period t, in constant January 1985 U.S. dollars;

CAP^t_i = production capacity at deposit i in period t;

and F_c = user-defined maximum capacity utilization rate.

Recycling is not relevant in the phosphate market, as phosphate rock is completely used up in application. However, the simulation model has been designed in a general fashion that will allow (in other mineral models to be built in the future) for an increment to supply from recycled and byproduct material.

Demand Determination

The demand side of the model is comprised of eight regional demands for fertilizer and two nonfertilizer markets. Econometric equations (*9*) have been derived for fertilizer demand, which is by far the largest portion (85 to 90 pct) of phosphate consumption (end use), while nonfertilizer demand is predeterimined by the user.

Consumption of P_2O_5 in fertilizer in the market balance model is the summation of solution values from statistically derived demand equations for the eight regions: United States, Canada, Central and South America, Africa, Asia and Oceania, Western Europe, Eastern Europe, and U.S.S.R. Each regional equation is of the form:

$$C^t_r = f(P^t_{superphos}, C^{t-1}_r, RFFR^t, API^t_r, pop^t_r, WPI^t, D_{1974}),$$

where C^t_r = consumption of P_2O_5 in fertilizer in region r in period t;

C^{t-1}_r = consumption of P_2O_5 in fertilizer in region r in previous period;

$P^t_{superphos}$ = U.S. gulf price of superphosphate in period t (currently set as $2.0 \cdot P^t_{US\ rock}$);

$RFFR^t$ = U.S. short-term Federal funds rate in period t;

API^t_r = agricultural production index for region r in period t;

pop^t_r = population in region r in period t;

WPI^t = U.S. wholesale price index for food in period t;

and D_{1974} = dummy variable for energy crisis.

The value for superphosphate price is computed as part of the yearly simulation. Values for all other explanatory variables are predetermined. The previous period's levels of regional consumption are part of the dynamic solution of the model. Projection period values for the exogenous data were calculated as time trends based on the historical data from 1964 to the present. Those variables that show no discernable trend, such as the U.S. short-term Federal funds rate, had forecast values set at their average values over the period.

The user can override the fertilizer consumption estimates from the equations by providing his/her own estimates of demand in future years. These user-provided demand numbers can be entered into the market balance model data base as a world total, in which case all regional demand equations are ignored, or the user can provide demand for only selected regions, in which case the remaining regions will have their demand levels estimated using the appropriate equations.

The nonfertilizer uses for phosphate are divided into two categories: mineral supplements for animal feed (4 to 5 pct of world phoshate rock demand) and industrial uses (6 to 7 pct of phosphate demand). Demand for P_2O_5 in animal feed supplements and industrial uses is added to the regional estimates of fertilizer demand to get total world demand for P_2O_5.

An assumption that demand for P_2O_5 in feed supplements will increase at 2.5 pct/yr was incorporated into the model. This assumption is based on potential market growth on a region-by-region level. The market for animal feed supplements is well established, perhaps even near saturation levels, in North America, Western Europe, and a handful of other developed countries, and only a low growth potential in this end use was seen for those regions. The U.S.S.R., Eastern Europe, and developing countries were seen as having far more growth potential.

About 70 pct of phosphate consumption in the industrial use category is as detergent builders and cleaners, and for water treatment. The forecast annual average growth for this end use of 3.5 pct was used in the market balance model. This growth rate is a continuation of the recent trend and assumes no further major move against phosphate in detergent after 1985.

Dynamic Model Solution

The method for converging to a price where supply and demand are in balance is a modified Newton-Raphson approximation technique (*28*). The technique first

establishes a lower bound and an upper bound for price. Successive iterations use estimated prices that are mathematically proven to narrow the difference between the lowest upper bound and the highest lower bound until convergence occurs.

The model uses year-specific values for many of the variables describing each deposit. All costs, feed grades, recoveries, and capacity numbers are year specific, for example. Values for these variables are reset automatically each time period as the model begins the iterative procedure to solve for an equilibrium supply, demand, and price in that year.

Resource depletion is accounted for each year as simulated production levels for each deposit are subtracted from the remaining resource estimate. When a deposit is completely depleted, it is no longer able to produce.

Undeveloped deposits are brought on-line in a timely fashion to maintain sufficient production capacity in future years. Each nonproducer deposit file data base is constructed so that the time necessary to develop that deposit is specified as a necessary preproduction development period. The method for determining when each nonproducer should begin the development process is a look-ahead function that computes an expected capacity-demand balance to see if a market niche exists for product from a new supply source.

The look-ahead function works in the following fashion. The number of necessary development years (N) is part of the property definition developed as part of the normal availability analysis. The look-ahead function makes an estimate of total future production capacity (in the year N + current) by adding up the capacities of all currently developed deposits that have sufficient reserves to carry them through to that year. It compares that estimate to an estimate of future demand calculated as a trend growth from current levels. If there is insufficient production capacity in year n, as measured by a user-determined critical value for the expected future capacity-demand ratio, then those deposits with the lowest total costs (as measured by the results from a 0-pct DCFROR analysis) are triggered to begin the development process. Properties are triggered in this lowest cost order until the appropriate balance of future capacity and future demand is established for year N + current. Those properties that are not triggered to develop are carried over into the same calculation for year N + 1 + current. For each year of the simulation the same set of calculations is made, establishing a pattern of property development that can maintain a supply-demand balance for all future years.

No reference is made to possible future price levels in the look-ahead function, and there is no guarantee that the incentives would exist that would lead property owners to develop in this manner. However, the balance model will report the cost levels associated with required new capacity, and those cost levels will be useful information in assessing likely future market conditions. Any development decision would, of course, depend on a company's assessment of the likelihood of capacity expansions by others and their total effect on the future balance of supply and demand.

Total Supply Definition

The major portion of potential supply is from deposits in MEC's. The market balance model determines production from each MEC deposit each period as a function of price, cost, and the associated capacity level.

The second component of supply is production from deposits in CPEC's: U.S.S.R., North Korea, Vietnam, and China. The projected supply from all CPEC deposits is derived outside the model and entered as a single value. The forecast of future phosphate rock production capacity for each of these countries is from an April 1985 study done by the British Sulfur Corp. for the Bureau of Mines (*2*). These forecasts were adjusted for average P_2O_5 content and checked for reasonableness by comparison with recent production trends. The deposit data base includes some information on deposits in these countries, but cost data are incomplete and non-MEC deposit cost evaluations are not performed. In any case, production decisions for CPEC deposits cannot be assumed to be based on the competitive model. The user can easily override the existing (default) values and substitute his/her own estimates of future production from CPEC deposits.

A third component of supply is production from small deposits in the United States that are not included separately in the model. These are largely elemental phosphate producers, and projected production levels are based on reported production levels in past years and on current and planned capacity levels. These deposits are excluded from the simulation model because they do not compete in the fertilizer market and do not respond directly to the price faced by phosphate rock producers who are supplying that market.

The final source of phosphate supply (also determined exogenously) is production from small deposits in foreign countries. This projection represents a continuation of production trends reported in the Bureau's Minerals Yearbooks. Production from these MEC sources has been substantially less than 1 pct of total world production in all recent years.

Several pieces of deposit-specific information are included in the revised deposit data set that feeds the market balance model. Many of these variables provide the user with the ability to impose a production level or development schedule on specific deposits about which he/she has information, for example, information on long-term contracts to supply material at agreed-upon levels (as reported in the literature for several companies). Occidental Chemical Co., which owns and operates the Suwannee River and Swift Creek operations in Florida, has an agreement to supply the U.S.S.R. with phosphate each year in exchange for ammonia. A second example relates to the Watson Mine (also in Florida), which is partially owned by a Japanese agricultural cooperative and appears to be providing a guaranteed amount of material to be exported to Japan. In both these instances, the contracted-for level of production is entered into the market balance model deposit data set as a minimum production level each year.

Minimum production levels may also be set for other reasons, such as the policy of government-owned operations to produce regardless of cost. Government-owned Brazilian operations, with a public stance of striving for self-sufficiency in fertilizers, are in this category.

If there is information that a particular (nonproducing) deposit will be a replacement property for a current producer when it depletes, this can be specified by the user. A property designated as a replacement candidate will not be allowed to begin production until the property it replaces has depleted.

For some deposits, the quality of the phosphate rock product may be such that it commands a premium over the current market price, or the product may be penalized

because of low quality or deleterious material. A multiplicative "price adjustment factor" for quality of the product allows a user to specify that a particular deposit faces a higher or lower market price than the standard solved for in the simulation

Output From the Market Balance Model

The principal outputs from a market balance model run include annual solution values for world demand, world supply, and the equilibrium phosphate rock price.

The total world demand value is consumption of thousand metric tons of P_2O_5 contained in fertilizer and nonfertilizer products, for all regions combined. Fertilizer demand can be reported separately for each of the eight regions. Consumption estimates for the two nonfertilizer uses are each single-value world totals. Total demand is defined as follows:

$$D_{total} = D_{fert\text{-}reg} + D_{ind} + D_{afs},$$

where D_{total} = total world consumption of P_2O_5 in all uses;

$D_{fert\text{-}reg}$ = the sum of consumption of P_2O_5 in fertilizer in the United States, Canada, Central and South America, Africa, Oceania and Asia, Western Europe, Eastern Europe, U.S.S.R.;

D_{ind} = consumption of P_2O_5 in industrial uses;

and D_{afs} = consumption of P_2O_5 in animal feed supplements.

The supply value is thousand metric tons of P_2O_5 contained in phosphate rock produced at all deposits combined. It is larger than demand by a constant factor that represents processing and handling losses. Total supply is defined as follows:

$$S_{total} = S_{MEC} + S_{USSR} + S_{China} + S_{Korea} + S_{Vietnam} + S_{other},$$

where S_{MEC} = total production from 206 MEC deposits;

S_{USSR}, S_{China}, S_{Korea}, $S_{Vietnam}$ = CPEC production;

and S_{other} = production from small deposits in MEC's not included in the simulation data base.

Supply estimates can be reported on a regional basis. Each regional total is a summation of production from all the producing deposits in that region. If production levels for any deposits are set by the user, those values are added into the regional and world totals just as if the model had solved for the production level. The set of regions reported automatically currently includes Western United States, Florida, total United States, Morocco, Jordan, Israel, Tunisia, other MEC's, CPEC's and total supply.

The price value in the summary table is approximately equal to the average variable costs at the producing property with the highest cost level. (The price will be less than the level that would cause the next highest cost property to begin production.) As such, it represents a minimum price that would likely prevail in the market. This reflects the usual assumption in a competitive market that facilities will produce up to the point where marginal revenue is equal to marginal cost. Properties that cannot sell their output at a price at least as high as their variable costs will shut down unless other factors come into play.

The price report includes values for all three prices used by the model. The U.S. price is in 1985 dollars per unit of P_2O_5 in phosphate rock. The world price used for foreign deposits is a translation of that value to represent the Casablanca price of P_2O_5 in phosphate rock. The demand price is the estimated U.S. gulf price per unit of P_2O_5 in triple superphosphate and is used in the regional demand equations.

The model's computer output also includes a reporting of all major adjustments to status on a property-by-property basis. Those changes include the triggering of a development decision for a nonproducer (i.e., the beginning of a countdown for the necessary number of preproduction years), the temporary shutdown of high-cost producing properties, the starting up of a new property, and the shutdown of properties because of resource depletion.

NETWORK FLOW

Introduction

One objective of the ongoing supply-demand project has been to develop a prototype mineral-supply model that draws upon the available wealth of deposit-specific data. A technique was required that could perform two tasks: (1) determine the optimal mix of production levels, by property, in a given economic climate and (2) determine optimal trade flow patterns on a region-by-region basis. An optimization model was deemed appropriate. It would utilize numerical techniques that permit the systematic screening of large numbers of alternative production levels and select those superior to others based upon a selection criterion. The selection criterion chosen was cost minimization.

The most common form of such mathematical models is linear programming (LP), mathematical problems characterized by linearity in both the objective function and the constraints. Since all LP-type problems are distinguished by the existence of various activities that compete for scarce resources, the goal is to determine the most efficient allocation of those scarce resources among competing activities. The objective of LP is to determine the level of each activity such that a linear criterion (objective function) is optimized subject to resource constraints.

While LP models are ubiquitous, they have certain drawbacks. The solution algorithms run fairly slowly on large problems. More important for this application, the design and objective of the model are virtually impossible to graph and difficult to summarize and interpret. For these reasons, the modeling method chosen was network flow programming, an optimization technique derived from LP. Thoroughly general networks, when matched with transportation algorithms, fulfill both of the previously mentioned requirements: (1) the optimal cost-minimization solution determines production levels by property necessary to fulfill a given demand level and (2) a feasible, optimal set of international trade flows are ascertained via the transportation algorithm. Generalized networks also overcome certain inherent failings in pure LP models: (1) the solution

algorithm can run up to 300 times faster than LP codes for similarly sized problems and (2) the model can be displayed graphically for expositional clarity (*19*).

An introduction to the economic rationale of the model, numerical techniques used, and applications are provided in the following sections. However, it is worthwhile, at this point, to mention the main features of the method and address the limitations.

General Description

The phosphate network flow model is based on the principle of technical economic efficiency: fulfill specified market requirements (demand) with the minimum use of resources, i.e., at the lowest opportunity cost. Demand in the model is either calculated automatically from an internal set of demand equations or set directly by the user. The supply side of the model is based on the interrelationships between the mining, milling, and acidulation facilities of phosphate-producing companies worldwide. Potential material flow or material processing is represented by arcs. Arcs connect nodes, which are aassigned to actual or hypothetical locations. Arcs are constrained by upper bounds and lower bounds; each arc has an associated cost. The upper bound is set at the maximum possible flow. The lower bound is set at the minimum required flow. Cost is set equal to the minimum of the average variable (marginal) costs of the activity that the arc represents. Oligopolistic, vertically integrated mineral market characteristics are incorporated into the model via these constraints and the intrinsic network design.

Mathematically, the model can be stated in vector notation as

$$\text{Min } \mathbf{cf},$$

subject to

$$\mathbf{Gf} = \mathbf{b}$$
$$0 \leqslant \mathbf{f} \leqslant \mathbf{u},$$

where $\mathbf{c}$ = vector of marginal costs;

$\mathbf{f}$ = vector of flows;

$\mathbf{G}$ = node-arc incidence matrix (constraint coefficient matrix);

$\mathbf{u}$ = vector of upper bound constraints;

and $\mathbf{b}$ = vector of node requirements (right-hand side, predetermined demand).

The network is optimized with a thoroughly general primal simplex algorithm (*29*) that attempts to fulfill predetermined demand at the minimum system cost, given the arc constraints.

A significant feature of the system is the ability to report material routing from original mining operation to final destinations of secondary product. Using the output from the thoroughly general network and given the arcs available, the network model system determines a feasible set of trade flow paths using a shortest path algorithm (*30*). The output of the path algorithm is sorted by destination and delivered-unit cost. This allows identification of the high-cost, or marginal, supplier of phosphoric acid in each region. The output is the basis for development of short-run supply curves for delivered secondary product, phosphoric acid, H_3PO_4. This capability is also used to predict shifts in trading patterns.

The network supply model is designed as a static optimization problem. That is, it solves a single year at a time. For multiyear analysis, the network can be solved serially with appropriate production and equilibrium price information passed forward from year to year. To the degree that time becomes a more important factor than short-run variable cost, a dynamic, or time-differentiated, optimization method (*31*) would be more appropriate.

An important issue that should be considered is the choice of decision criteria. While there is nothing inherently wrong with selecting a decision criterion that emphasizes producing output with the minimum use of inputs (cost minimization), it is not the only valid criterion on which production decisions can be made. Other goals, such as the maintenance of market share, maximization of the life of the mine, or infrastructure development (in the case of government-owned properties) are sometimes pursued (*32*). However, it is extremely difficult to quantify noncost goals, which are often called satisficing goals (*33*). To the extent that goals other than cost minimization exist in any geographic region, they must be considered when the network solution is evaluated.

A related consequence of the modeling method and the decision criterion selected is that market economic conditions are postulated. World regions dominated by MEC's are assumed to act in a rational economic manner, to make choices based on the desire to minimize opportunity cost; however, this is not necessarily the actual case. In those regions where price is not a major determining factor of the level of demand or where accurate cost information is unavailable, the solution to the model must be forced and is necessarily suspect. Therefore, short-run supply curves for certain regions (e.g., the U.S.S.R., East Europe) are not calculated.

Another issue that should be addressed concerns the transportation algorithm solution. A feasible, optimal set of paths from source to sink can be determined, but not *the* single most optimal set of paths. As a result, it is useful to compare several transportation algorithm solutions when doing scenario analysis. While the set of paths will be similar in each solution, they will not be identical. The solutions indicate only what could happen, not absolutely what will happen.

The final major issue related to the network supply system is the data requirements. Networks are extremely data intensive, both in terms of quality and quantity. Although the need for accurate data is not by definition a shortcoming, it may limit the number and type of mineral models developed. And if a model is to be of continuing use, the input data must be kept current. Conversely, improvements in collection and availability of data are often observed when the relevance of the model to decision making is demonstrated.

Basic Network Design

The phosphate network supply system has as its core a mathematical model of the world phosphate industry, the intrinsic design of which is introduced here. The selection of mining and milling properties, secondary processing plants, and ports for inclusion in the network will be discussed, along with a description of how each is incorporated into the design. The base case for the network flow model attempts to incorporate the majority of known paths of

material flow for each active phosphate property in the world as of 1984. Background information for design of the network was found in Bureau deposit reports, trade journal and magazine articles, published trading statistics, and personal interviews with numerous industry and Bureau personnel.

A full range of mineral facilities are represented individually as discrete nodes for each property in the network flow model. These include mines, beneficiation plants, calciners, wet-process acidulation plants, ports, and other transportation depots. Arcs that connect the nodes represent the opportunity for processing or flow of material. A continuous set of arcs from source of supply (a mine or inventory stockpile) to final demand (a regional phosphate rock, phosphoric acid, or inventory demand node) is referred to as a "path." Units of flow throughout the network are consistently metric tons of contained phosphorus pentoxide (P_2O_5); however, flow of P_2O_5 in phosphate rock and P_2O_5 in phosphoric acid are never represented by the same arc. Rather, they are separated into distinct flows on distinct arcs. As a result, there could be two arcs connecting the same pair of ports, one for phosphate rock flow and one for phosphoric acid flow.

The network has been designed in blocks, each of which comprises the operations of a specific company or country. A hypothetical network block is shown in figure E-4. Several of the locations are shown as numbered circles to facilitate understanding the flows. Properties or countries are further grouped in regional blocks, with the regions interconnected to replicate international trade routes. Phosphate rock and phosphoric acid production can fulfill demand either intraregionally or in any region with which there are trading connections.

Phosphate mining properties included in the model were selected from the Minerals Availability Program data base using the following criteria (in addition to the property-selection criteria outlined in the availability methodology section in appendix D.).

1. Include all significant phosphate properties in MEC's that are supplying ore to the fertilizer market and are or have been producing in the last 5 yr (unless resources were depleted by 1984).
2. Include all significant phosphate properties in MEC's that are currently developing or are expected to be developed within the next 20 yr.
3. Exclude properties in CPEC's, owing to lack of adequate data.
4. Exclude byproduct production from iron mines.
5. Exclude production from extremely small mines and deposits.
6. Exclude depleted properties shipping material from stockpiles.

Data on domestic and foreign properties include information on the mine (or mines) at each property, the

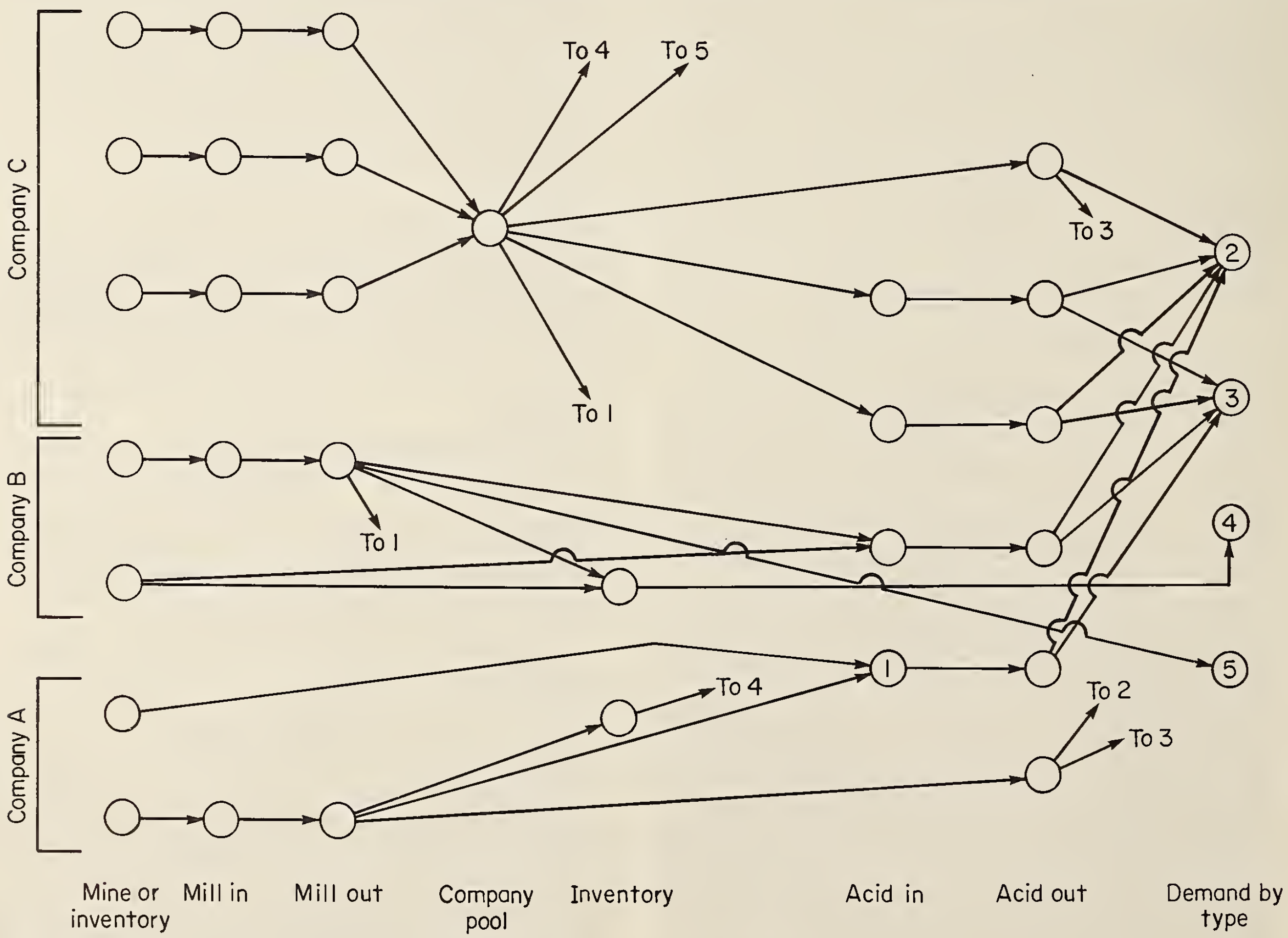

FIGURE E-4. — Sample network schematic.

associated mills, and ports fed by each mine. Node names were assigned to each process step or location. A strict naming convention has been followed to ensure consistency and identifiability. Node names are 16 characters long. The first 12 characters are taken from the property or location name utilizing a phonetic word-condensing algorithm. The last four characters are a suffix used to identify the process or product associated with the node. Table E-1 lists the various suffix types. For example, the node name for the entrance (or feed point) to Moroccan phosphoric acid plant Maroc Chemie I is "MAROC CHEM I AI".

Table E-1.—Node process and product identifiers

Suffix	*Meaning*
ACD	Phosphoric acid.
AI	Acid plant entrance.
AO	Acid plant exit.
CALO	Calciner exit.
D	Demand.
DRY	Dried phosphate rock
INV	Inventory.
RK	Phosphate rock.
ML	Mill entrance.
MLO	Mill exit.
MN	Mine entrance.
MNO	Mine exit.
POOL	Country or company pool
WET	Wet phosphate rock.

Node and Arc Layout

Nodes are connected by arcs, each representing the opportunity for processing or transportation (illustrated in figure E-4). For example, an arc connecting an "AI" node to an "AO" node would represent a wet-process phosphoric acid plant. An arc connecting an "RK" node to another "RK" node would represent a transportation link. These paths of potential flow are constructed from the mine to each successive destination, including all alternative destinations. If output from a mine can be shipped to any of three different calciners, arcs will be constructed to all three. Similarly, if several mines ship ore to a specific mill, arcs will be constructed from all the mines to that mill even if the production from any one would be adequate to run the mill at capacity. As an example: phosphate rock output from the Big Four (AMAX) mill flowed to two phosphoric acid plants, Piney Point (AMAX) and Plant City (Central Farmers). Arcs were therefore constructed from Big Four to those plants.

Active mines are viewed as the main potential source of supply, with previous-period inventories of phosphate rock the secondary source. Each mine is represented separately in the model. Inventories are aggregated at the company level in the United States but are not further differentiated by grade or origin as these statistics are not fully reported to the Bureau. As a result, a company that operates three mines and probably has at least three distinct stockpiles (if not more) will be described as having only one stockpile. Phosphate rock inventories outside the United States are reported by the International Fertilizer Industry Association (IFA) for seven countries. Although there are undoubtedly numerous other stockpiles in the world, only those for which there are reasonably reliable statistics are included in the model.

Each of eight world regions is presumed to have some demand for phosphate rock for use in animal feeds, detergents, or as direct-application fertilizer, and for phosphoric acid, which is used as a proxy for all phosphate fertilizers. In addition, certain individual companies and countries are assigned demand nodes for end-of-period phosphate rock inventories.

Mills, calciners, ports, etc. are viewed as transshipment points. They do not supply phosphate to the system, nor do they demand phosphate for final use. The model does not currently address the possibility that inventories of ore, phosphate rock, or partially beneficiated product might be stored at any or all locations.

In some instances, mill or calciner output and previous-period inventories are directed to a company or country phosphate rock pool, a feature incorporated into the network to facilitate design rather than to suggest that all production of a corporate entity is physically collected at a single location. The phosphate rock pool (or mill if no pool is associated with the producer) is subsequently linked to neighboring phosphoric acid plants. Connections are also available from the pool or mill to one of three destinations: (1) end-of-period regional or company inventory demand, (2) regional phosphate rock demand, or (3) a local port. In countries with more than one producing property (and without an artificial phosphate rock pool node), all phosphate rock output is directed to a single port. From there, regional inventory or phosphate rock demand nodes as well as non-adjacent phosphoric acid plants are reached. The purpose of these design features is to facilitate identification of individual country flows and thereby assist the analyst using the network flow model.

Wet-process phosphoric acid plants included in the model were selected from a list provided by the IFA (*22*). The selection criteria were as follows:

1. Include all plants currently operating.
2. Include all plants operating or idle in 1984.
3. Include all plants expected to open within the next 10 yr.
4. Include plants in non-MEC regions at zero cost, to the degree that reliable capacity data are available.

Phosphoric acid plants are fed either by locally produced phosphate rock or by imported phosphate rock. Many countries that do not mine phosphate rock do process phosphate rock into phosphoric acid. These phosphoric acid plants are included in the model, and all phosphate rock imported as feed to a specific plant or plants flows through the same central port. For example, the United Kingdom has six phosphoric acid plants but mines no phosphates. Phosphate rock for use in these plants is necessarily imported. Arcs have been placed in the network linking the port for each actual or potential exporter to Liverpool, the port selected for Great Britain (other ports in Great Britain may actually have phosphate rock import flow, but Liverpool was selected as the only one for the network for simplicity.) From Liverpool, arcs are included to each of the phosphoric acid plants. Some countries both mine and import phosphate rock. In such instances, the network is designed to allow the phosphoric acid plant to accept feed either from local mills or from the port through which phosphate rock imports flow.

Output from a phosphoric acid plant can flow to two possible locations: to a port for export or to the regional phosphoric acid demand node. In instances where several plants are producing in the same country, the output from them all is directed to a single port. From there, material can go to either regional demand or export markets. Again, the reason for this arrangement is so that the analyst using the network can more easily interpret the solution flows. Appendix B lists all phosphoric acid plants included in the model as well as several that were excluded for specific reasons.

Ports and railheads were chosen to reflect actual shipping locations to as large an extent as was feasible; however, major ports were selected to represent many smaller surrounding ports to limit the number of nodes and arcs in the model. Most countries were assigned a single port location; a few, such as the United States, were allowed more than one port. Ports are differentiated by type of phosphate product, so a single physical location could appear twice in the model, once as a transshipment point for phosphate rock and again as a transshipment point for acid. Ports are linked to other ports in a design that replicates reported or assumed trading patterns. Not every exporter is linked to every importer. Further, exporters serving importing countries with more than one port listed in the model will be linked to only one of those ports. This is done for two reasons. First, it facilitates control of intercountry flows. Second, the network solution algorithm will always choose the cheapest path available, making the alternative paths superfluous.

Information on trading has been gleaned from trade journals, the Bureau's 1984 Minerals Yearbook (*7*), and various IFA publications (*12-14, 21-22*). In addition, transportation data was acquired from numerous issues of "Phosphorus and Potassium"[2] and "Industrial Minerals,"[3] and "Distances Between Ports" (*34*).

To recapitulate, the model can be thought of as a set of demands for phosphate rock, phosphoric acid, and phosphate rock inventory that can be filled from any one or several of the many supply locations around the world. The ability of any region to supply product to another is limited by accessibility, reserves, capacity, cost, and political considerations. The first and last of these constraints are design issues. The remaining three are addressed in the following section on constraint values.

Network Constraints

As previously stated, nodes are connected by arcs that represent the opportunity for material flow. Viewing the network in the context of LP, arcs represent variables and nodes correspond to constraints. The ability to represent network problems as arcs and nodes results from the characteristic that each ordinary variable (arc) has exactly two coefficients (multipliers) and so appears in two constraints (*29*). One coefficient is associated with the tail node and another with the head node of each arc. They are used to augment or diminish flow over the arc and to control the direction of flow.

Node Constraints

Nodes represent constraints due to the principle of conservation of flow; flow into a node always equals flow out of a node (*35*). A single constraint equation incorporates all flows associated with a given node. The variables on the left-hand side (LHS) represent the individual arcs feeding into or flowing out of the node. The constant on the right-hand side (RHS) reflects the resource limitation imposed on the node. The coefficients attendant on each variable in this equation are positive if the arc enters the node and negative if it leaves the node. These are the structural constraints, which are linear and normally expressed as equalities.

If flow is conserved over the arc (all flow leaving the tail node reaches the head node), the head node has a coefficient equal to 1 and the tail node has a coefficient equaling −1. However, certain head node multipliers in the network flow model are assigned positive values less than 1. The value assigned arises from the fact that mineral recovery systems always have a degree of process loss. Some percentage of the total ore body is left in the ground; ore falls off the conveyor belt; flotation recovers most but not all of the contained mineral. In each of these instances, the amount of flow entering the process is more than the amount leaving the process. The amount of flow reported as available to the next downstream facility should be the actual amount recovered from the process, not the total available before process losses are taken into account. The head node multiplier can be used to represent these losses quite realistically.

Consider mill recovery as an example. Some total tonnage of mineral contained in ore is fed into the mill and processed. The milling cost per ton should apply to the total feed, but less than this amount will be recovered. By assigning a multiplier equal to mill recovery to the head node of the arc representing milling, flow out of the arc can be decreased to the appropriate level. Each process arc in the network flow model has multipliers assigned in this manner. In the case of wet-process acidulation, the multiplier associated with all plants in the model is 0.87. This value was chosen as representative of the average level of recovery associated with the production of phosphatic fertilizers.

The nodes associated with inventory stockpiles have negative external flow; i.e., the RHS of the constraint associated with an inventory supply node has a value less than zero because flow equal to the RHS is entering the system. The assigned value equals ending inventories in the previous time period. As this is a fixed rather than variable value, the constraint is an equality.

Actual end-of-period phosphate rock inventory is reported by U.S. producers to the Bureau of Mines and is published by IFA (*36-37*) for some foreign producers. In the 1984 simulation, inventory demand is set to these reported values. The constraint is written as an equality, with the RHS a positive number.

The model can be used to project changes in inventory levels, given specified levels of phosphate rock and phosphoric acid demand. This is accomplished by forcing production at mining properties and changing the inventory demand constraints to inequalities. Inventory demand no longer equals a set value but rather is less than or equal to a very large number. If production exceeds demand, inventories will increase in less cost-competitive regions.

The constraint equations for mining nodes are written as inequalities since the mine can supply P_2O_5 at a rate equal to its annual capacity or at some lesser rate; i.e., supply from mines is variable rather than fixed. The RHS of the equation is equal to the total economic reserves of the mine. This number is calculated in the following manner:

$$TER = (RES \cdot MR \cdot 1/(1\text{-}DIL)) \cdot GR,$$

where TER = total economic reserves;
RES = in situ resource;
MR = mine recovery factor;
DIL = dilution factor;
and GR = average ore grade.

Inequality constraints that are written as "less than or equal to" are converted to equalities through the use of slack variables. In networks, slack variables are called slack

[2] British Sulphur Corp. Ltd., London, England.
[3] Metal Bulletin Journals Ltd., London, England.

arcs and represent unused resources when the RHS constant represents available resources. Slack variables do not appear in the objective function since they contribute nothing to the optimal solution criterion. Slack arcs appear in only one constraint equation as the tail and head nodes of the arc are identical. On a slack arc, the multiplier associated with the tail node is +1 and with the head node, 0.

Demand levels are assumed fixed for any single year and are handled in the model as equality constraints with positive RHS values because flow is leaving the system. Values were calculated for the base year from references *12, 14,* and *21*.

On the basis of numbers reported in these publications, a world balance of P_2O_5 was calculated for 1984. Demand levels for phosphate as rock, as fertilizer, and as rock for inventories were set at quantities calculated via a world material balance. The basic form of the calculation is shown below. Positive values indicate additions to the system or supplies; negative values are removals from the system or demand levels. All quantities are in metric tons of contained P_2O_5 and represent 1984 values.

Rock production
\+ Beginning inventories
\+ Rock imports

Available rock
− Ending inventories
− Nonfertilizer consumption

Rock for acid
− 13.1 pct production loss

Available acid
\+ Imported acid
− Exported acid
− Domestic acid consumption

Other disappearances

This calculation was completed separately for each of the eight world regions in the network flow model, and demand levels were determined from the results. Demand for phosphate as fertilizer was set equal to domestic fertilizer consumption as reported by IFA (*21*). Demand for phosphate rock was set equal to nonfertilizer consumption plus "Other disappearances." The beginning and ending inventory values were those reported to IFA (*36-37*) and the Bureau (*7*). One final adjustment was made to the initial numbers. In those regions where direct application of phosphate rock is prevalent, a percentage of phosphate-as-fertilizer demand was shifted to phosphate rock demand. Estimates of direct-application levels were provided by IFA (*21*). Demand values are reported in table E-2.

The residual value in the calculation "Other disappearances" deserves some comment. All regions showed some level of other disappearances, ranging from less than 1 pct in the United States to 20 pct for Eastern Europe. They can be accounted for in several ways. It is reasonable to assume that reporting standards are not uniform worldwide. This could result in misinterpretation of some numbers or an outright lack of information. Also, IFA reports an average phosphate rock grade for each country but builds its phosphate rock statistics tables on metric tons of phosphate rock shipments. To the degree that phosphate rock grade differs from the reported average, the material balance will be biased toward underreportage or overreportage of production and shipments. Finally, there is the issue of material handling losses. These are extremely difficult to quantify on a country-by-country basis and, as a result, are not directly accounted for in the model.

Table E-2.—Demand values used in network flow model simulation for 1984

Demand node	*Quantity, mt P_2O_5*
Africa ACD	928,400
Africa RK	266,500
Algeria INV	23,332
Asia ACD	7,104,000
Asia RK	1,704,877
Canada ACD	777,679
Canada RK	281,699
Eastern Europe ACD	1,975,000
Eastern Europe RK	1,160,000
Egypt INV	54,500
Israel INV	61,438
Morocco INV	1,835,430
Senegal INV	201,913
South Africa INV	410,642
South America ACD	1,751,000
South America RK	490,000
Togo INV	30,492
Tunisia INV	309,170
U.S.S.R. ACD	5,900,000
U.S.S.R. RK	1,250,000
United States ACD	4,066,543
United States INV	3,330,488
United States RK	1,320,294
Western Europe ACD	5,217,500
Western Europe RK	1,960,000

A base year network solution should reflect actual industry actions as accurately as possible so that it can serve as a point of comparison for sensitivity analysis. For that reason, IFA numbers rather than values predicted by demand equations were used. In subsequent simulations, total regional phosphoric acid demand would be a number predicted by an appropriate regional demand equation.

Finally, the RHS value for the constraints associated with transshipment nodes is zero as no flow enters the system or leaves the system at the node.

Capacity Constraints

In addition to node constraints, variables in the network flow model have capacity constraints. Each variable (arc) has an associated upper bound and lower bound. The upper bound represents the maximum allowable single-period flow over the arc in terms of metric tons of contained P_2O_5. The lower bound represents the minimum required single-period flow. Because the problem is solved with a primal-simplex-type algorithm, lower bounds are actually adjusted to zero during solution and then readjusted; however, this process is invisible to the user.

Capacity constraints are written as two equations, one for the upper bound and one for the upper bound. For all arcs other than supply or demand arcs, flow is less than or equal to the upper bound and greater than or equal to the lower bound. Table E-3 delineates upper and lower bound decision criteria by arc type.

The bounds on slack variables are handled in a slightly different manner. The upper bound on slack arcs associated with active mines is set at total economic reserves for the life of the mine. The only other arc connected to the mining node is the mining process arc, which has an upper bound equal to annual mine capacity in terms of P_2O_5. The slack arc permits supply to vary from zero to the upper bound of the mining process arc. The slack arc is constrained by total reserves rather than annual reserves to facilitate multiyear simulations, an issue discussed later. Initially, slack arcs associated with nonproducing mine nodes are assigned an upper bound value of zero. When the mines are redefined as producers, the upper bound is reset to total

Table E-3.—Arc bound criteria

(Ordinary variables)

Arc activity	Upper bound	Lower bound
Mining	Annual mine capacity in metric tons of contained P_2O_5.	Zero unless set equal to known contractual obligations.
Milling	Annual mill capacity in metric tons of contained P_2O_5.	Do.
Acidulation	Annual acid plant capacity in metric tons of P_2O_5.	Do.
Transportation from mill or acid plant to port or pool.	Annual plant capacity in metric tons of P_2O_5.	Zero.
Transportation port to port.	Arbitrary large number unless set equal to reported trading levels in metric tons of P_2O_5.	Do.
Transportation port to acid plant.	Annual acid plant capacity in metric tons of P_2O_5.	Do.
Port or pool to regional demand node.	Total annual capacity of plants feeding port or pool unless set equal to reported consumption levels.	Zero unless set equal to reported consumption.

economic reserves.

The capacity constraints for supply ordinary arcs, which are equalities, are written as—flow is less than or equal to minus a constant and flow is greater than or equal to minus a constant, where the constant is available supply. Supply slack arcs are inequalities, the capacity constraint equations for which are written as—flow is less than or equal to minus the lower bound and flow is greater than or equal to minus the upper bound. Demand ordinary and slack arc equations are written similarly except that the RHS is a positive value.

Arc Costs

Associated with each arc is a number that represents the average variable cost of moving one unit of contained P_2O_5 over the arc. Variable costs are assumed equal to marginal costs for reasons discussed in detail below. For mining and milling, costs in January 1985 U.S. dollars are updated values from the data base developed for the availability portion of the report. Operating cost categories included in variable cost for mining and milling are—

- Supervisory labor,
- Skilled labor,
- Unskilled labor,
- Electric power,
- Fuel (diesel, gas, etc.),
- Supplies (nonenergy),
- Equipment repair parts,
- Administration and general overhead,
- Severance taxes,
- Royalties.

These costs are used in the model after correction to reflect level of contained P_2O_5. Operating cost is divided by average feed grade for the simulation year. The general equation for mining cost is shown below. Milling costs are developed in a similar manner.

$$\frac{\text{Mine operating cost per metric ton ore}}{\text{percentage } P_2O_5 \text{ in ore}}$$

$$= \text{arc cost per metric ton } P_2O_5.$$

Short-run average variable cost (SAVC) is normally described as a parabola. The validity of this assumption for the mineral industry is worth considering. The U-shaped SAVC curve demonstrates a single minimum cost point often referred to as "capacity." However, plants are actually designed with reserve capacity above average production to allow the firm to respond to seasonal changes in demand (*38*). Over this reserve capacity, short-run marginal cost (SMC) equals SAVC and both are at a constant level per unit of production. To the left, SAVC is decreasing as quantity increases, reflecting underutilization of the fixed capital and increasing marginal physical product (MPP) of variable factors. To the right, SAVC and SMC are rising, reflecting decreasing MPP brought on by overutilization of capital (which increases breakdowns and therefore raises maintenance costs) and overworked labor (*39*).

Suggesting a single minimum cost point also ignores the fact that production is a flow over time. If the costs of shutdown and subsequent startup are not significant, then output becomes a function of operation time as well as operation rate. Given that the plant operates within its rated capacity range if it operates at all, the SAVC and SMC for each unit of production would be constant. Total costs would be represented over this range by a straight line with a positive slope. Production below and above capacity would result in higher costs because of changing marginal productivity. In this case the SAVC curve is better described by a truncated parabola as previously shown in figure E-2.

The phosphate industry is an illustrative example. Wash plants, mills, and beneficiation plants are almost never run at rates far less than capacity. Normally, when plants are in operation, they run 24 h per day, 7 days per week. To limit production, phosphate mining companies reduce the total number of running days per year. The plants may run full time for 8 or 10 months and then shut down for the remainder of the year. Alternatively, they may be operated full time for 10 days, then shut down for 4 days. This 10-on, 4-off schedule can continue for all or part of the year (*1*) and is presently being utilized by various Florida producers. In combination with total shutdown, the on-off schedule makes possible enormous flexibility in annual output at constant average variable and marginal cost. The result is that average variable cost for mines and beneficiation plants can be used as a proxy for marginal cost. This is an important point as the supply curve for each firm is, by definition, marginal cost at or above the minimum average variable cost.

U.S. transportation costs are based on rail and barge rates reported to the Bureau by individual phosphate producers. Costs are corrected to reflect both contained P_2O_5 in either phosphate rock or phosphoric acid as necessary, and where appropriate, a distinction is made between wet and dry rock haulage costs. Costs for international ocean transport of phosphates have been derived from freight rates published in various issues of "Phosphorus and Potassium" and "Industrial Minerals." All internationally transported phosphate rock is assumed to be dried. A total of 470 data points were collected. The functional form of the relationship is described as

rate = r(distance, intensity of use, passage through canals).

These were transformed to the log form:

log rate = f[log distance, index of shipping, binary 1, binary 2].

Distance between ports in nautical miles was found in a publication of the Defense Mapping Agency (*34*). (Spellings of ports in the network flow model conform to spellings in this publication.) The index of shipping is published by Chartering Annual (*40*) and comprises a weighted average of costs over different routes for different commodities. The index of shipping is a measure of relative shipping activity worldwide. As such, it is a useful proxy for demand-influenced changes in shipping rates. The binary variables represent the two major canals, Suez and Panama. Binary 1 variable is 1 if the shipping route requires passage through the Suez Canal and 0 otherwise. Binary 2 variable represents the Panama Canal in a similar manner. The ordinary least squares regression is as follows:

$$\begin{aligned}\text{log rate} = &-1.998 + 0.469 \text{ log distance}\\ &(-7.185)\quad(13.874)\\ &+ 0.003 \text{ ship index} + 0.333 \text{ binary } 1\\ &\quad(14.292)\qquad\qquad(12.307)\\ &+ 0.281 \text{ binary } 2\\ &\quad(5.722)\end{aligned}$$

$R^2 = 0.8187$

F-statistic = 525.959.

(T-statistics are shown in parentheses below each coefficient.)

Costs of acidulation are derived with variable costs in 1981 dollars for phosphoric acid plants worldwide. These costs were updated to January 1985 dollars using the Bureau's international mining cost indexation system. These variable costs are reported in terms of metric tons of P_2O_5 processed and are summed to obtain unit cost per ton of contained P_2O_5 in wet-process phosphoric acid.

Previous years' inventories were judged to be costless as they reflect previous years' expenditures and are thus sunk costs. No holding costs for inventories are included for two reasons. First, most phosphate companies simply store phosphate rock in piles exposed to the elements, which is not a costly endeavor. Second, any holding costs that are incurred are not reported, and as a result, defensible estimates are unavailable.

Solution Algorithms, Output, and Interpretation

A network flow model is a constrained optimization that can be described as fulfilling demand while minimizing the per-unit cost times units of flow over all arcs without violating the node and arc constraints placed on the system.

This problem is solved via a thoroughly generalized network algorithm (GN2MD) that utilizes a phase I-phase II start and progresses toward optimality in the following manner. Imaginary arcs (artificial variables) are introduced and form the basis for an initial feasible solution. During phase I, cost is set to zero on all real variables and a cost of 1 is assigned to imaginary variables. Using the primal simplex method, real variables are found to accept the flow from the starting imaginary variables. As flow on an artificial variable falls to zero, that variable is removed from the problem. When all flows have been shifted to real variables, phase I is complete; i.e., there is a set of flows entirely on real variables. This represents a feasible, albeit a nonoptimal solution. At the start of phase II, actual costs are restored to the real variables. The primal simplex method is again applied to find better (lower cost) flows. When no more flow can be shifted to alternative lower cost arcs, an optimal solution has been found. The solution fulfills technical efficiency since the technical limitations of the market (constraints) are observed, and it fulfills economic efficiency because output is supplied at the lowest system cost.

The code utilized by the model is extremely streamlined, requiring significantly fewer iterations and calculations than previous generalized network codes. There are two important benefits derived from this streamlining. First, the program runs faster. Second, fewer numerical operations mean increased numerical stability.

The solution to GN2MD is provided in three parts: (1) the objective function value, (2) the optimal flows by arc, and (3) the "shadow price" associated with each constraint.

The first of these is a single dollar value equaling the minimum total system cost required to fulfill predetermined demand. The optimal value for the 1984 base case is utilized as a point of reference. In subsequent runs of the model, the optimal value can be compared to the original base case value to determine, other things being equal, how a change to the network flow model would impact total cost.

For the second, optimal-solution arc flows are defined as the predicted level of flow in metric tons of P_2O_5 for each arc and are segregated into two types, nonbasic and basic. Arcs that have an optimal flow equal to either zero, the lower bound, or the upper bound are nonbasic arcs. Arcs with an optimal flow between zero and the upper bound are basic arcs. There is a maximum of one basic arc for each node. (These flows can be reported together or separately as desired.)

It is important to keep in mind that the network flow model is solved with a cost-minimizing algorithm; hence, the simultaneous solution represents a systemwide cost minimization as opposed to cost minimization for any single property. Every individual flow is a function of the cost and constraints not only on that arc but also on all other arcs. The solution flows represent the optimal results if the economic world were "rational" and "efficient" and only cost-minimizing goals were taken into consideration. As a result, flows can be viewed in two different but interrelated contexts. The levels of flow into a single destination (head node) from several competing sources (tail nodes) are indicative of the relative competitive status of each of the suppliers into that market. Simultaneously, the levels of flow from a single source (tail node) to several destinations are indicative of the relative attractiveness of each of the alternative markets.

To compare the relative competitive position of several suppliers in a single market, it is necessary to compare the optimal flow on each incoming arc with the capacity constraints on that arc. For example, if three arcs are directed into a single port, each corresponding to a different source country, it is possible to rank the three source countries in terms of relative competitiveness. If the optimal flow on one arc is at zero units, then that supplier is relatively less competitive than other possible suppliers. Conversely, if optimal flow on another of the arcs is at the upper bound, then that supplier is relatively more competitive than suppliers whose optimal flow is not at the upper bound constraint. Suppliers for whom the optimal solution is between the upper and lower bound have an intermediate competitive position, above those suppliers with flow at zero and below those with flow at the upper bound.

These results can be explained in terms of economic efficiency, but to do so requires the use of the third part of the solution, the shadow prices. Each node in the network is assigned a shadow price "pi" (or node potential) as part of the optimal solution. Pi represents the value to the system of a unit of flow added to the network at that node. In other words, pi represents the amount by which the objective function value would change if the RHS value of a node constraint were increased by 1 unit.

Once the shadow price at each node has been determined, the rules of complementary slackness are used to identify which arcs should have increased flow (*41*). Where cost minimization is the objective, c_{ij} is the cost on arc ij, m_i is the arc multiplier at node i (or G matrix coefficient for arc constraint i), and m_j is the arc multiplier at node j, the complementary slackness rules are

1. If c_{ij} is less than $pi_i m_i + pi_j m_j$, it is profitable for arc ij to increase its flow, and in fact, the unit increase in profitability or marginal profit is $pi_i m_i + pi_j m_j - c_{ij}$.
2. If c_{ij} equals $pi_i m_i + pi_j m_j$, increase or decrease of flow on arc ij does not effect the objective function value.
3. If c_{ij} is greater than $pi_i m_i + pi_j m_j$, it is profitable to decrease flow on arc ij.

The rules of complementary slackness state that if the increase in value of a unit of flow as a result of moving from the tail to the head node is greater than the cost of doing so, then it is economically efficient to do so. Conversely, if the increase in value of a unit of flow as a result of moving from the tail node to the head node is less than the cost of doing so, no units should be moved. A supplier can be considered relatively more competitive in a specific market to the degree that flow from that source is economically efficient compared to flow from other suppliers. (As stated previously, the model assumes rational cost-minimizing economic behavior.)

Consider an arc with optimal flow at the upper bound. Flow has been set to the upper bound because it is efficient to do so; i.e., the difference in shadow price at the head node versus the tail node is greater than the unit cost associated with the arc. If optimal flow is set at the lower bound, then the marginal arc cost is greater than the potential increase in shadow price, so it would be inefficient to have flow on the arc. Flow would be greater than zero on such an arc only when the lower bound forces flow. If flow is between the lower and the upper bounds, cost equals the potential change in value and the model is indifferent as to level of flow.

If multiple arcs are solving at the upper bound, suppliers can still be ranked by competitive position through the use of sensitivity analysis. Flow out of the head node representing the market in question is incrementally reduced and the network flow model solved with GN2MD. As this process is repeated, the reduction in total flow out of the head node forces flow from the highest cost supplier to that node to be reduced to the lower bound. Eventually all suppliers but one have been reduced to the lower bound. Similarly, if several suppliers are shipping at the lower bound into a single node, their relative competitive status can be ranked by reversing this process. Flow through the head node can be increased and the model solved again until each of the nonshippers has been assigned flow.

Transportation Algorithm Output and Interpretation

The initial optimal solution discussed above (as distinguished from sensitivity analyses) is used to develop regional short-run supply curves for delivered secondary product. A short-run industry supply curve is a schedule of the amount of product all firms are willing and able to offer for sale at each cost and is represented by the horizontal summation of the individual marginal cost curves for each firm. In this model, the quantity-marginal cost relationship representing supply is derived by determining the marginal supplier to each region for a range of quantitiy levels. The marginal supplier will have an associated marginal cost per unit of delivered secondary product, which is the sum of the arc costs for all arcs in the path from mine to demand point. As was previously discussed, arc costs are considered marginal costs and so a sum of the arc costs over a path is identical to the marginal cost for a unit of delivered product. The marginal supplier is defined as that supplier with the highest marginal cost to a particular demand node. As such, it would be the first supplier to lose market share if demand were reduced.

Because of the complexity of the network design, both in terms of number of nodes and direction of flow, it is impossible to identify all the paths from mine to demand point by visual examination of the model. Rather, the marginal supplier is identified through the use of the transportation algorithm. This algorithm takes into consideration the combinatorial complications arising from the nondiscrete nature of generalized network flows and is applied to the optimal data set from the generalized network solution.

Paths are selected in the following manner, with the goal of identifying the alternative distribution paths compatible with the least cost solution. That is, paths must use the optimal network solution. Arcs for which the optimal flow is zero are automatically excluded from the set of possible arcs available to the transportation algorithm. The program then solves for the shortest path from every source to every destination. A simple first-in, first-out (FIFO) shortest path algorithm is used. (Approximately 10 pct of the nodes are sources and 3 pct destinations.) The program next selects the minimum, or shortest, path distance to each destination as calculated above and sends as much flow as possible (consistent with the optimal solution) along those paths, storing them in memory. Since the algorithm is working only with optimal flows, sending all available flow is consistent with the optimal solution. The optimal flows are reduced by the path flow just recorded in memory. This process is repeated until there are no more flows left for which paths are needed. At this point the problem is finished.

Paths are reported by region, by demand type, in order of increasing marginal cost. The most expensive path to each demand type in each region is flagged as a marginal path. The marginal cost on the marginal path is paired with the demand quantity for the associated demand node as the price-quantity coordinate. Output will be as follows:

1. A list of all supply paths (s) for each D_{rji}, sorted in order of increasing MC_{ri} for each year in the simulation;

2. A list of the marginal paths for each D_{ri} and the associated MC*,

given $i = 1,\ldots,8$ demand regions,
$j = 1,\ldots,m$ demand levels,
$r = 1,2$ demand type,
$s = 0,\ldots,n$ supply paths,
D = demand,
MC = marginal cost,
MC* = marginal cost on the marginal path.

One output of the model is a graph of unit cost for delivered product versus cumulative quantity, for all paths

to a single destination (see the "Supply" section for examples). A graph allows the user to visually compare the cost-quantity relationships for all suppliers to a single demand region. This is particularly useful in sensitivity analysis, allowing visual comparison of the cost of suppliers under differing scenarios.

It is important to keep in mind that the transportation solution is guaranteed to be optimal but not to be uniquely optimal. By nature of the design of thoroughly general networks, more than one optimum is possible. (Therefore, the marginal supplier should be viewed as a proxy for the actual marginal supplier.)

To develop the vector of price-quantity coordinates that will be used to represent supply, it is necessary to repeat the foregoing process of determining marginal suppliers by region for a series of different demand levels. These demand levels could be calculated from the demand equations for each region. For a given scenario, i.e., network design, all variables in the demand equation are fixed by the user, except for price and quantity. By varying price, a series of quantities can be calculated. This process is repeated for each of the eight demand regions, using the same set of prices. The result is an array of price-quantity coordinates for phosphate fertilizer demand in each of the regions. These quantity levels are substituted into the network design. For any single solution, all demand levels reflect the same hypothetical market price.

Once a vector of price-quantity pairs representing supply has been calculated for each region, these values are regressed to calculate the short-run supply curve for delivered secondary product. A robust regression that minimizes the absolute deviations is used rather than an ordinary least squares regression. The regression is formulated as a dual linear program, using an appropriate translation of the variables, to have a dual feasible starting basis. The final LP solution values can be recovered and translated to yield the parameters defining the robust regression equation.

Multiyear Analysis

The network flow model can be used for multiyear analysis. For future years, demand for phosphoric acid (as a proxy for fertilizer demand) can be set by the user or determined via the demand equations. Demand for phosphate rock is set at a constant for any single simulation year. For forecasting, phosphate rock demand is prespecified or is increased each year by a percentage set by the user. In the base year, this demand has been calculated from information on usage published by IFA (*21*). Inventory demand in the base year is that reported by IFA and various U.S. manufacturers. For forecasting simulations, changes in inventory demand are set by the user. No demand equations have been developed for nonfertilizer or inventory demand, and no attempt has been made to create supply curves for those products.

The previously mentioned regression equation representing supply and the equation representing demand can be solved simultaneously to generate a short-run equilibrium price and quantity. This should *not* be viewed as a price forecast. Since the model is variable cost based, return to capital is not part of the solution value but would certainly impact pricing decisions. The equilibrium price and quantity values have several important uses. Equilibrium price values calculated in sensitivity analyses can be compared with base year values to give an indication of possible relative movement of price with respect to market changes. The equilibrium values could also be used to select that generalized network solution for which demand levels are closest to equilibrium quantity. Once the appropriate solution is identified, production levels by property, relative competitive status into specific markets, and marginal suppliers could be identified and reported separately for each year in the analysis.

The individual production levels identified through use of the current-year price-quantity equilibrium are used to reduce economic reserves of each property prior to the simulation of the next year of the multiyear analysis. As a property's economic reserves are reduced to zero, it no longer can supply the network. Exhaustion of reserves is modeled in this manner.

Nonproducers are considered for reclassification as producers between each year of a multiyear run. The criteria for changing a property to producer status are listed below. A positive response to any one of the four would trigger the change.

1. Reserves at another mine (specified by the user) are exhausted.
2. Equilibrium price in the previous time period equals or exceeds a price specified by the user.
3. Equilibrium quantity in the previous time period equals or exceeds a quantity specified by the user.
4. The simulation year is a prespecified year.

All nonproducing properties have default values for each of these criteria; however, each can be changed by the user. To bring properties into the simulation, the upper bound on the slack supply arc associated with that property's mining node is reset to equal economic reserves. This does not mean that a property will automatically operate; the cost-minimizing algorithm chooses who will produce and at what level. Reclassifying a property merely provides the opportunity to produce.

Sensitivity to Data and Design

It is important to reiterate that the network flow model is a cost-minimization model. As with all optimization models, it is only as reliable as the data inputs to the model. Further, it is more sensitive to some inputs than to others. This sensitivity will now be considered.

Flow in the network flow model is designated as metric tons of contained P_2O_5. To reduce cost values to contained mineral, the operating costs are divided by the appropriate grade. Over arcs with process losses, cost is further divided by the recovery factor. Consider the following path from mine to final demand node:

> Mine, mill, (RK) port of origin, (RK) destination port, acid plant, (ACD) port of origin, (ACD) destination port, regional demand node.

To calculate the cost over this path, mine operating cost plus mill operating cost are divided by mill recovery. (These costs have been divided by average grade before inclusion in the model.) The result is added to transportation costs and acidulation costs, and this new subtotal is divided by the phosphoric acid plant recovery factor. Finally, phosphoric acid transportation cost is added to obtain the final path cost. By definition, costs are directly impacted by the ore grade and by the recovery factors used in the model. This seems appropriate for an engineering-based model. It allows an enormous amount of flexibility in testing the effects of alternative engineering parameters.

However, the impact of inaccurate grade or recovery factor selection may be emphasized in the results. Consider, for example, a mine with a reported average ore grade of 22 pct P_2O_5, and a mill recovery factor of 0.70. Assume that the mine operating cost to be used in the network is \$30/mt. If ore grade were 10 pct higher (or 24.2 pct), mine operating cost would be \$27/mt or approximately 10 pct lower. Similarly, a 10 pct change in recovery factor, from 0.70 to 0.77, would reduce mine and mill costs by 10 pct. A 10-pct decrease in either the ore grade or the recovery factor would increase operating cost by 10 pct (to \$33/mt).

If this 10-pct reduction (or increase) in cost were to make the mine and mill less (more) expensive than the next best alternative path available in the network (other things being equal), relative production levels in the optimal solution would change. The point is that cost changes are important *in relation to other costs*. If all costs were increased by 10 pct, the optimal arc flows would not change. Only the objective function value and total unit costs would change.

The impact of cost changes is also a function of the percentage of total path cost that a single arc represents. For example, costs on acidulation arcs are high relative to costs on mine and mill arcs. A 10-pct change in the cost of such an arc, which by itself represents up to 30 pct of the cost of a single path, will be more likely to cause a change in the optimal solution than will a 10-pct change in an arc representing a smaller percentage of the total path cost. As a result, the model is particularly sensitive to changes in transportation costs and acidulation costs, as well as average grade and recovery factors.

The model is also sensitive to constraints. As previously discussed, part of the optimal solution is the shadow price of the constraint. If the shadow price is positive, the objective function value would be increased by increasing flow at the node. If the shadow price is negative, objective function value would be decreased by increasing flow. Since the objective is to minimize cost, flow should be increased at those nodes with a negative shadow price as long as the cost of increasing the flow is less than the shadow price. A change in such a node constraint will alter the optimal solution.